The neurobiology of speech and reading

Kenneth R. Pugh, PhD

President and Director of Research,
Haskins Laboratories

Professor, University of Connecticut

Associate Professor, Yale University

Outline of topics

1) The neural basis of speech and reading

2) Bi-directional relations between speech and reading(an individual differences perspective)

3) Cross language reading research: Is there a universal reading circuitry?

Learning to read is unlike learning the spoken language

- Speech is a biological specialization
  Reading is a product of culture

- Preschool children pick up speech on the fly
  They recognize 10,000 words by ear before they can read

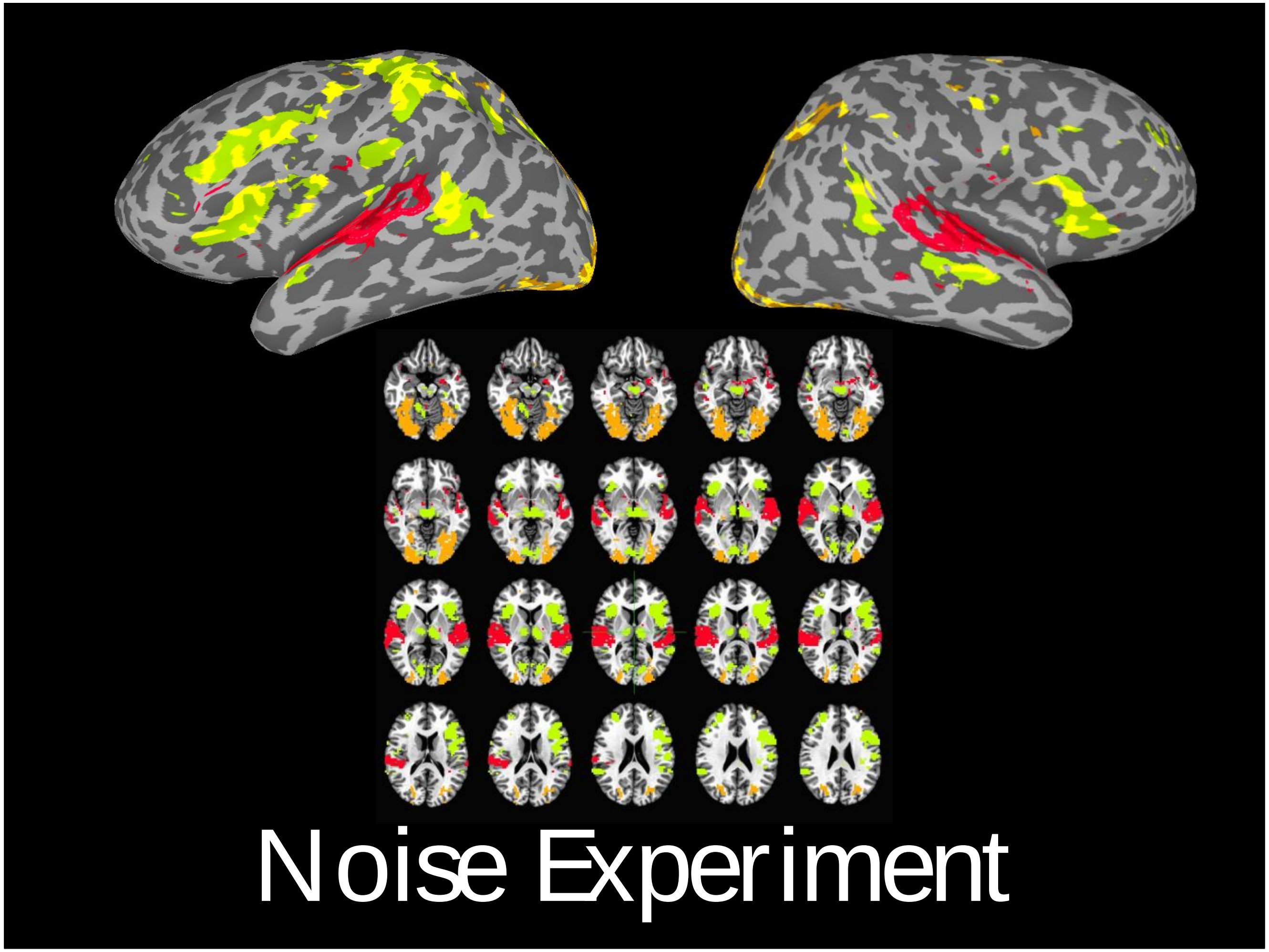
- Unlike speech, reading generally requires instruction to promote phonological awareness

Reading is an exercise in “neuronal recycling” (Dehaene, 2010)

- Reading provides a fertile domain in which to study
  - Learning
  - Perception (vision, hearing)
  - Memory
  - Language
  - Brain bases of cognition

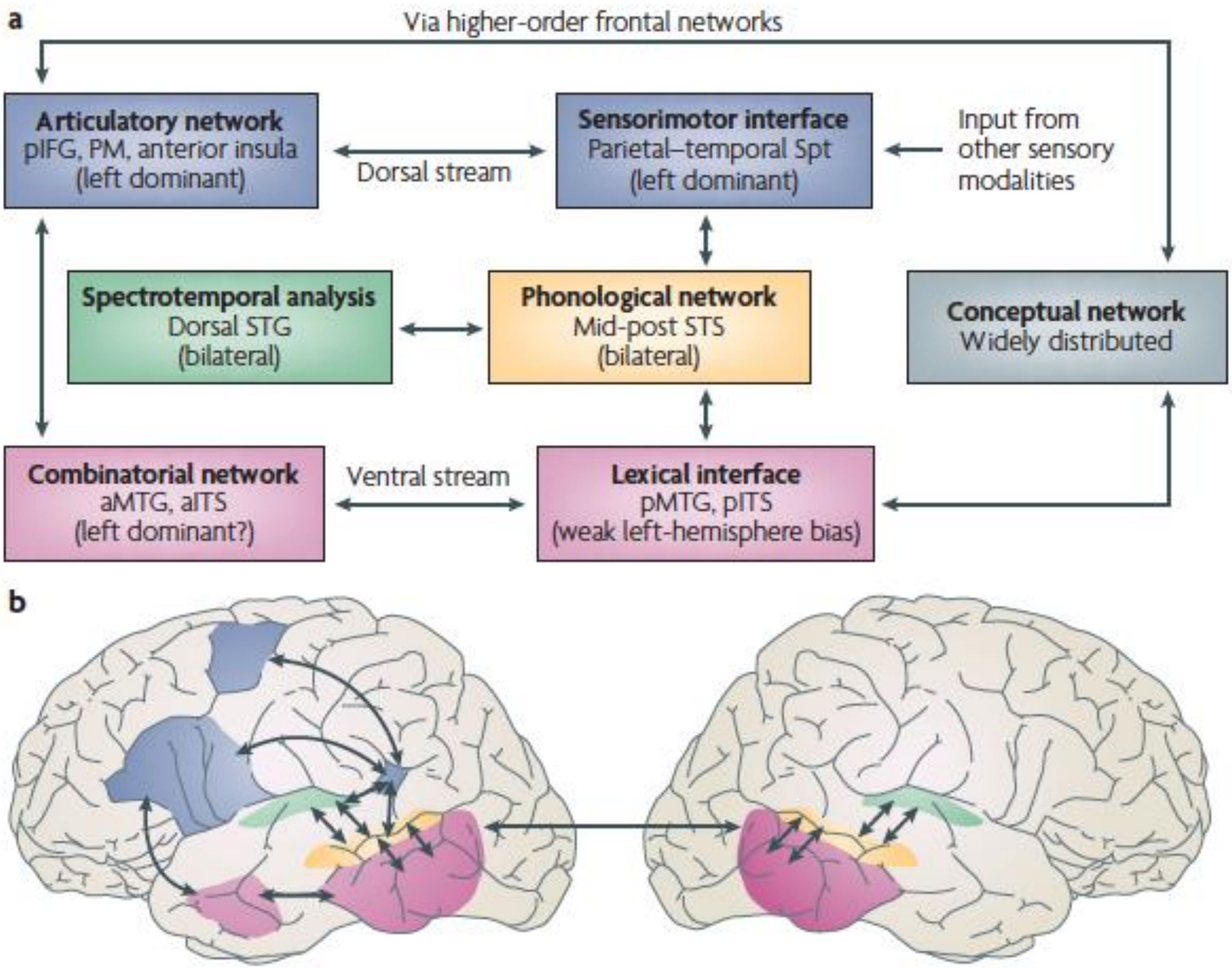
How are spoken and written language represented in the brain?

Print vs. speech



Speech and brain

Hickok & Poeppel,2004



Perception/production interactions in speech

- Feedforward and feedback auditory-motor systems are critical in both speech processing and in speech adaptive learning.

Guenther; 2006

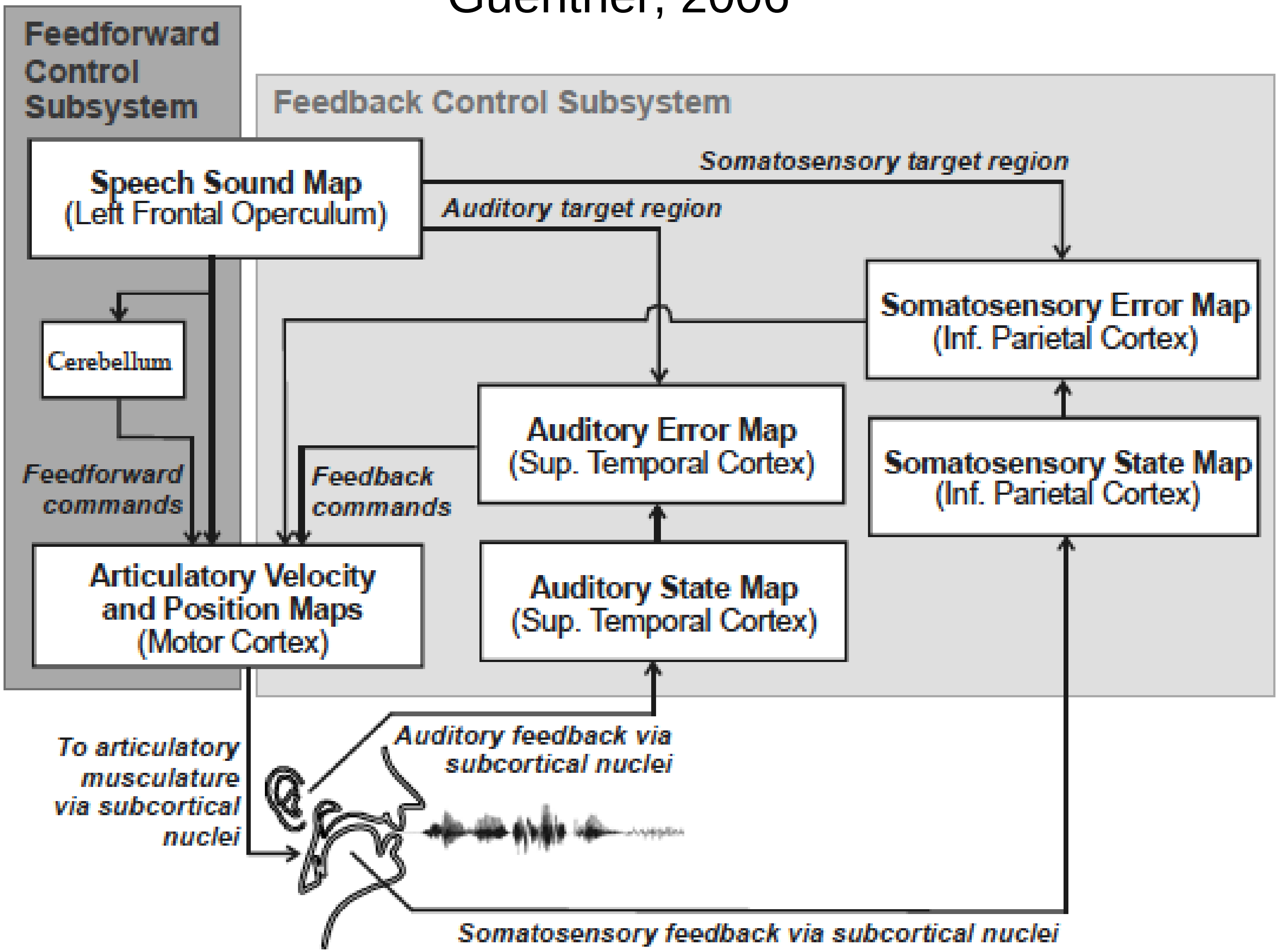


Figure 1. Schematic of the DIVA model of speech acquisition and production. Projections to and from the cerebellum are simplified for clarity.

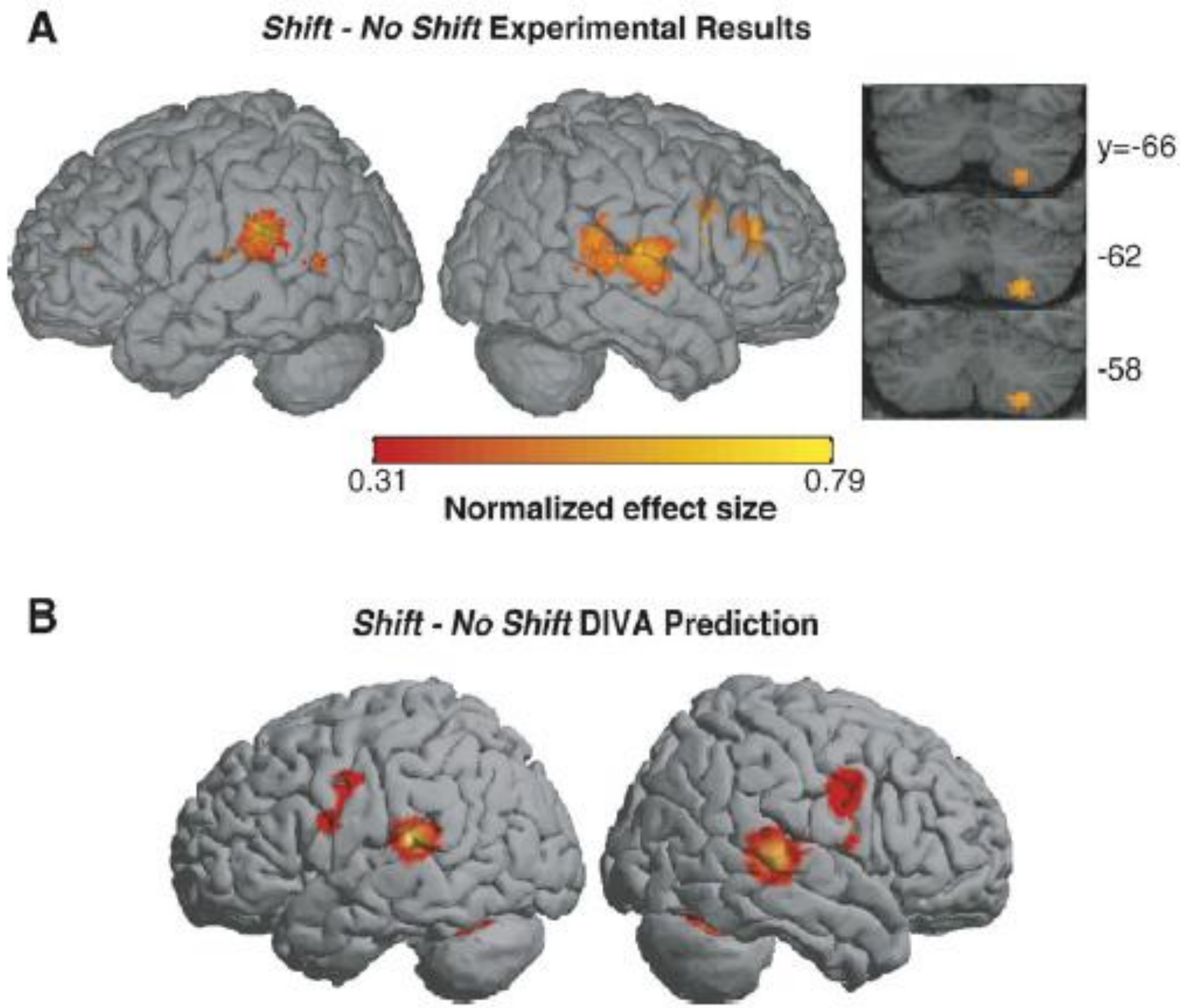
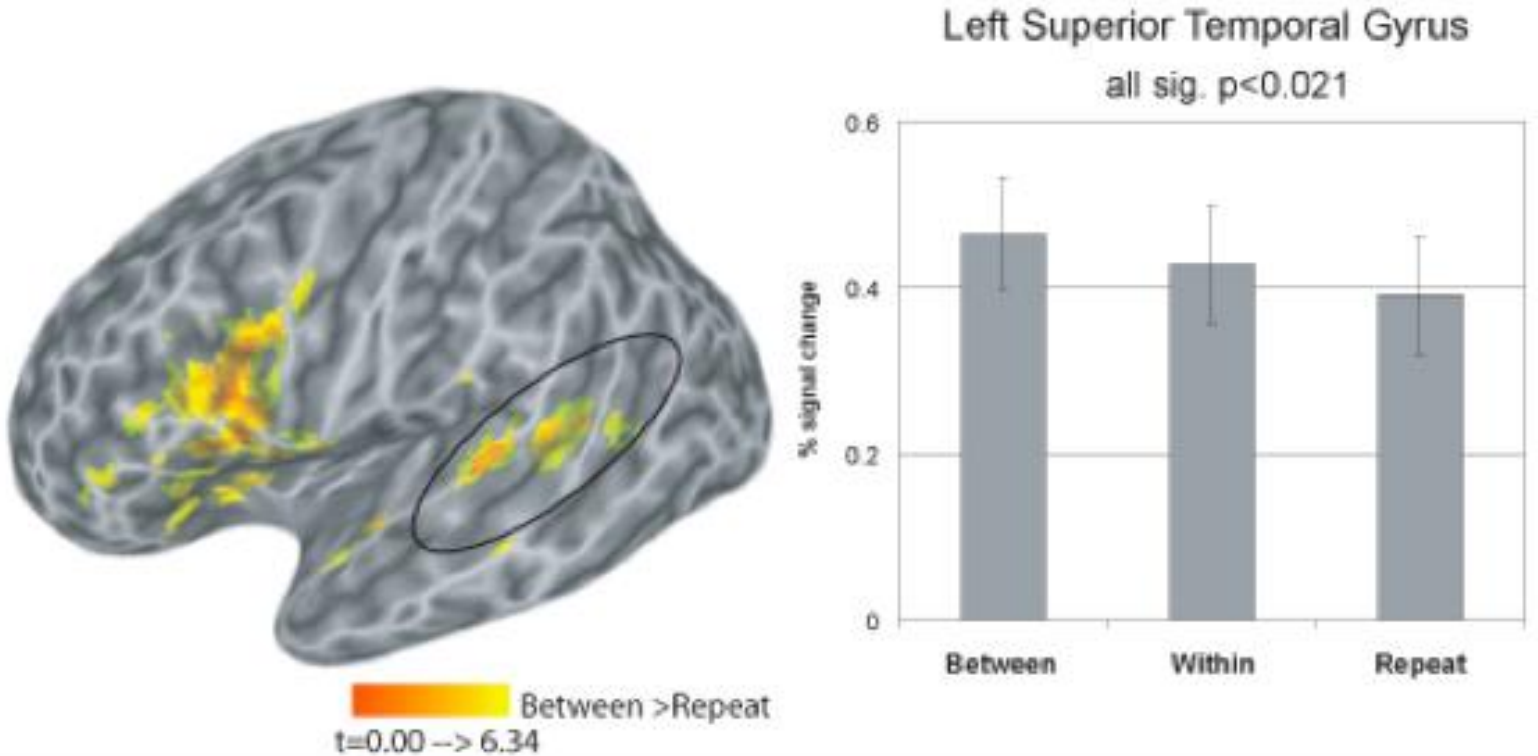


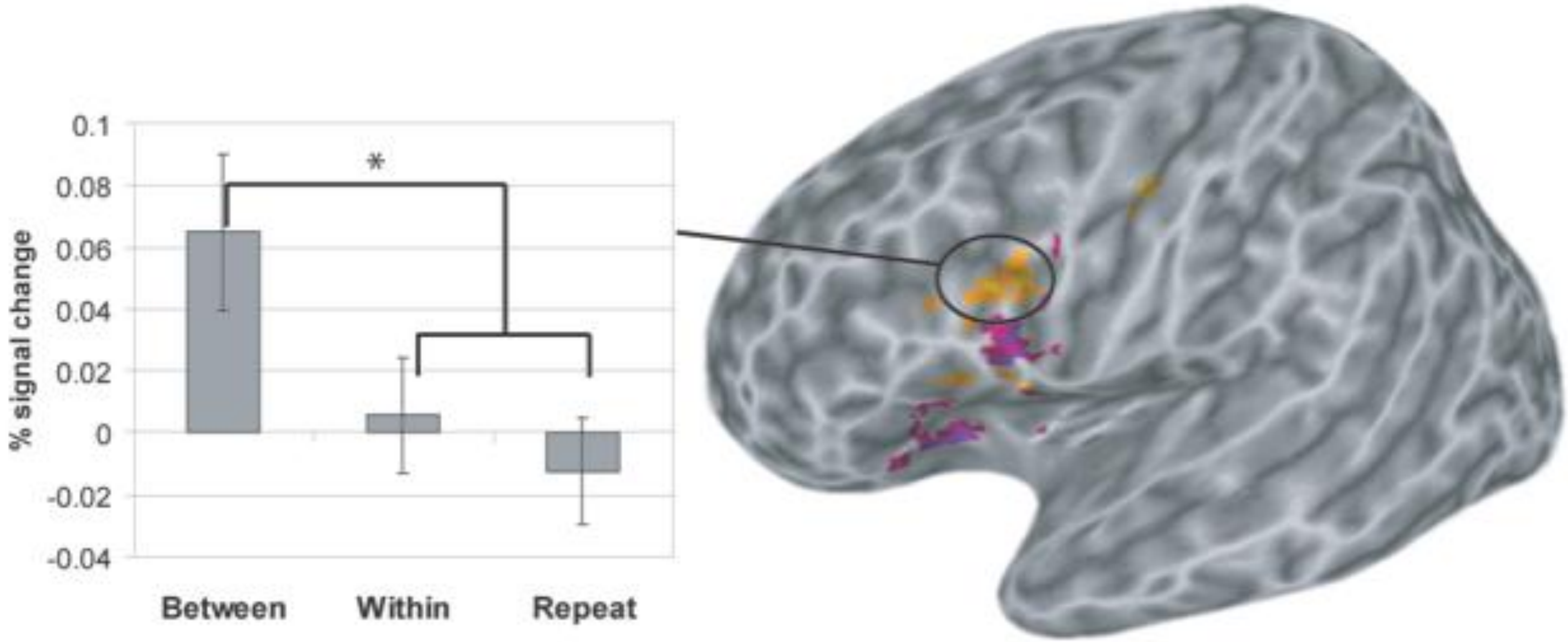
Fig. 4. BOLD responses in the *shift* – *no shift* contrast. (A) Map of statistically significant normalized effect sizes (voxel threshold: $t>3.10$; $df=5488$;

Invariant Responses to Phonetic Category Variability?



- ✦ Graded response to between/within-category variation in left STG

(Myers, et al. 2009)



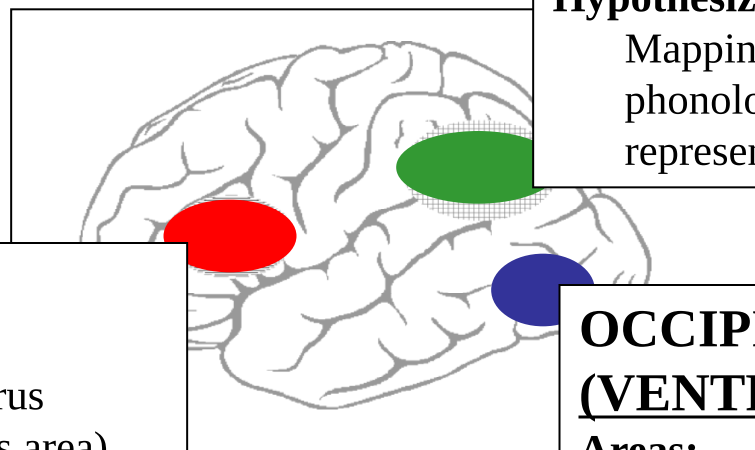
✦ "Invariant" (all/none) response to phonetic category change in left IFG/Precentral Gyrus

(Myers, et al. 2009)

Reading and brain

An initial reading model for alphabetic languages

(Pugh et al. 2000,2010)



TEMPOROPARIETAL <u>(DORSAL)</u>

Areas:

supramarginal, angular, superior temporal (Wernicke's) gyri

Hypothesized Function:

Mapping of orthographic to phonological and semantic representations

<u>ANTERIOR</u>

Areas:

inferior frontal gyrus (including Broca's area)

Hypothesized Function:

Articulatory recoding

OCCIPITOTEMPORAL <u>(VENTRAL)</u>

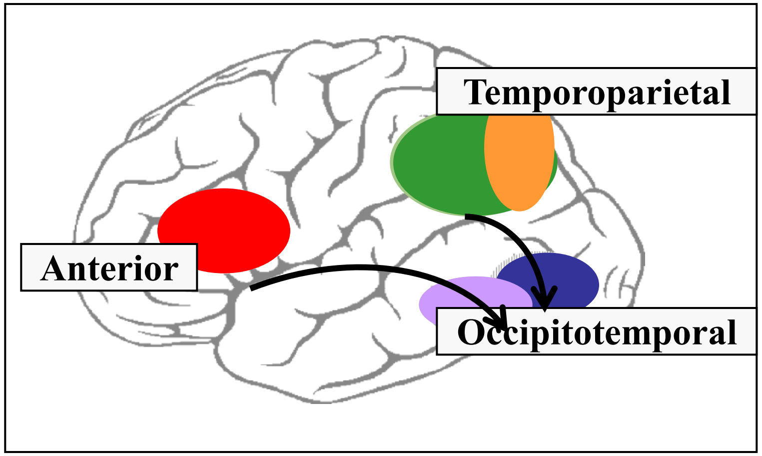
Areas:

occipitotemporal juncture, middle and inferior temporal gyri

Hypothesized Function:

Linguistically structured memory-based word identification system (posterior aspect = "word-form" area)

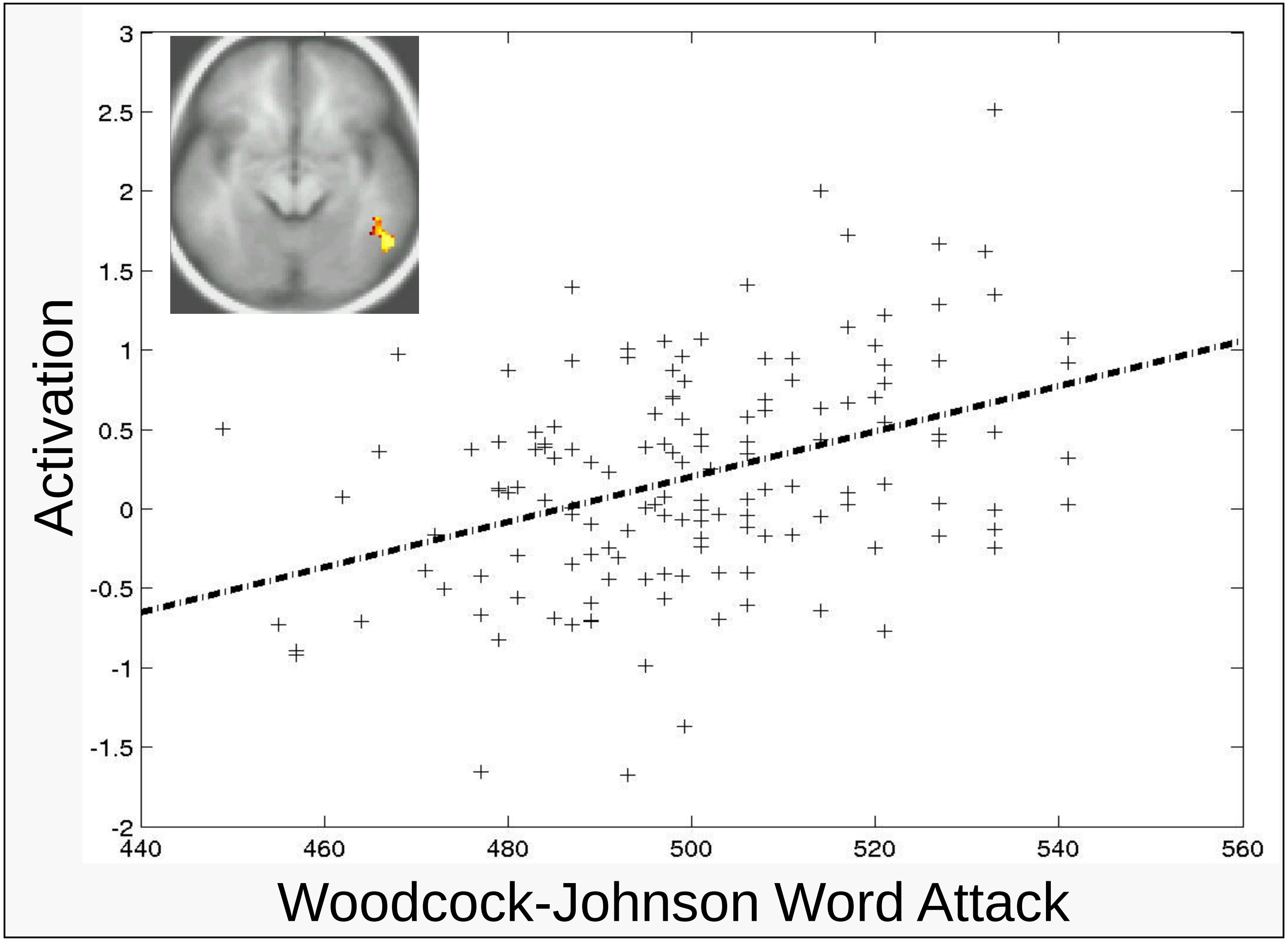
Neurotrajectories in Reading Development



- Increases in reading skill are associated with increased specialization of ventral LH areas for print (Shaywitz, Shaywitz, Pugh, et al., 2002, Booth et al., 2001, Church et al., 2008)

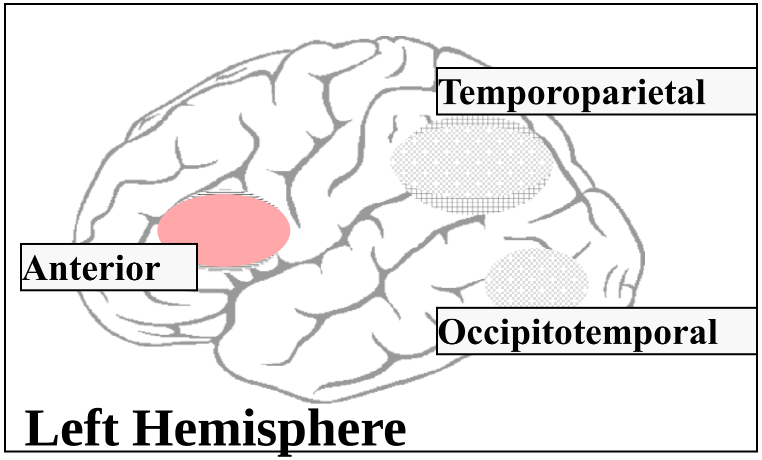
Reading Development: VWFA and age/skill

(Shaywitz, Shaywitz, Pugh et al., 2002, *Biological Psychiatry*)



Brain circuits and Reading Disability

- Frequent finding: A large number of studies indicate that RD readers tend to **under-activate both LH temporoparietal and LH ventral (occipitotemporal)** regions during reading and language tasks; this has been seen in several languages to date (Paulesu et al., 2001;Wu et al. 2010).
- **RH and frontal "compensatory" shift in RD often reported**



Reading disability and brain: summary of current neuroimaging findings

Functional/structural neuroimaging indicate that poor readers, especially reading disabled (RD) children, adolescents, and adults fail to organize left hemisphere (LH) temporoparietal (TP) and occipitotemporal (OT) cortical regions into a coherent reading circuit (Pugh et al., 2000; 2008; 2010; 2012):

1) Unstable and reduced activation

2) Reduced functional connectivity

3) problems in online adaptive learning, and consolidation of this learning (Pugh et al., 2008)

4) Reduced grey and white matter volumes

Bi-directional relations between reading and speech: Effects of literacy on speech

Castro-Caldas et al., 1998

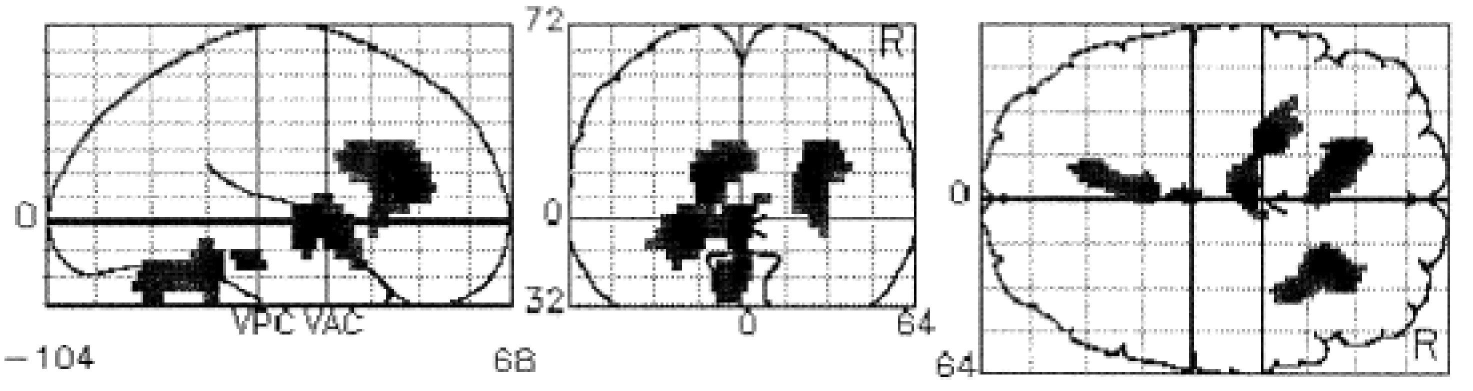
Table 1 *Rate of successful repetitions of words and pseudowords during scanning*

Group	Word repetition	Pseudoword repetition	Paired *t* test
Illiterate	110 ± 7	39.5 ± 13	$P < 0.00001$
Literate	118 ± 1	100 ± 19	n.s.
Mann–Whitney *U* test	$P < 0.005$	$P < 0.005$	

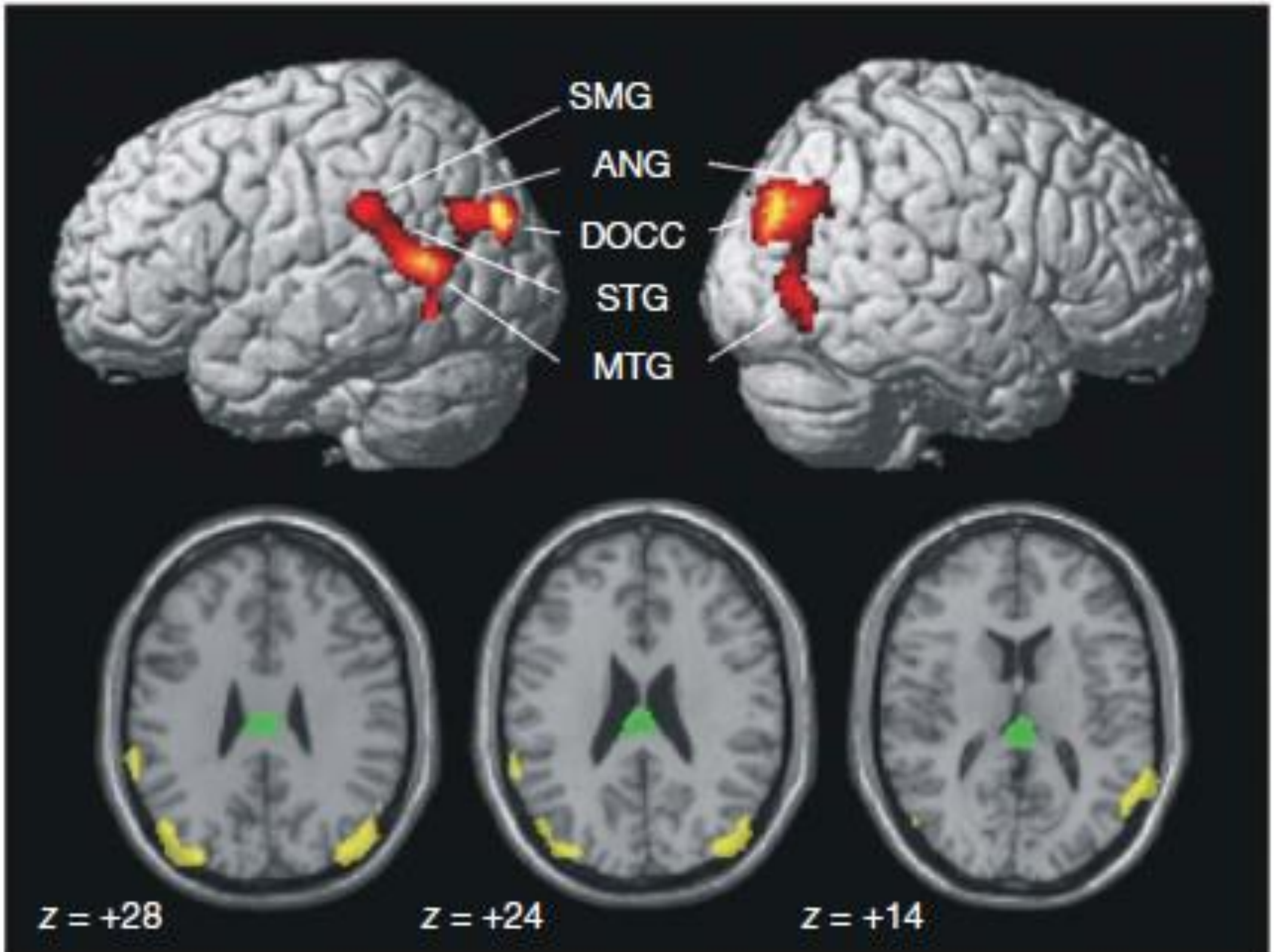
Maximum total score was 120 for each collection of lists; correct repetition was scored 1, and 0 otherwise. n.s. = not significant.

Castro-Caldas et al., 1998

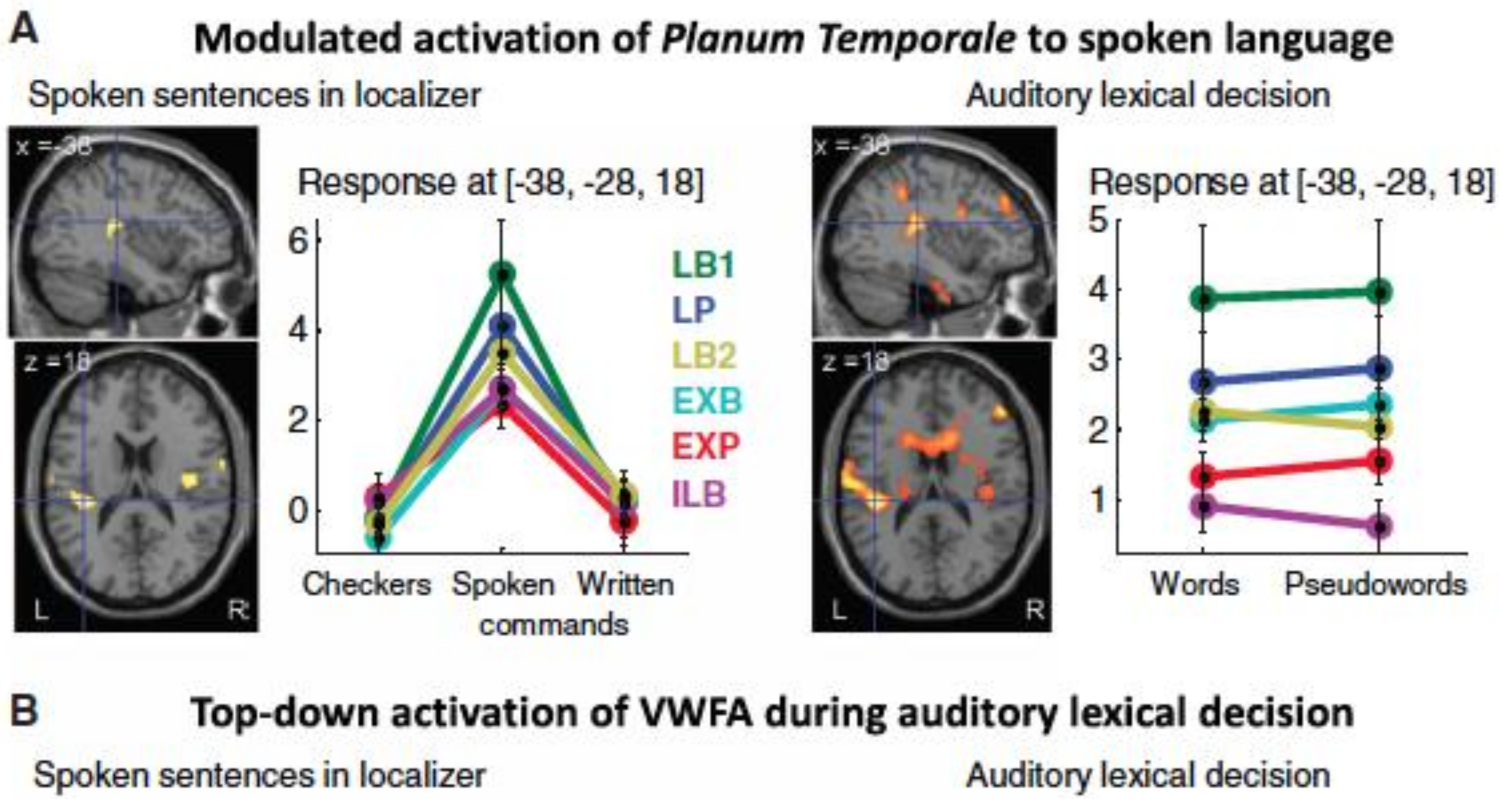
(F)



Carreiras et al, 2009



Dehaene et al., 2010



Bi-directional relations between reading and speech: Effects of speech on literacy acquisition

- A good deal of research indicates that early receptive and expressive language development predicts individual differences in reading outcomes.

Haskins/Yale longitudinal projects

We recently conducted two NICHD-funded longitudinal studies asking:

- What are the behavioral and neurobiological preconditions for successful reading acquisition?

- Study 1) from 7-9 years examines at risk children with multiple levels of analysis (genetics, neuroanatomy, neurochemistry, neurocircuitry, behavior).

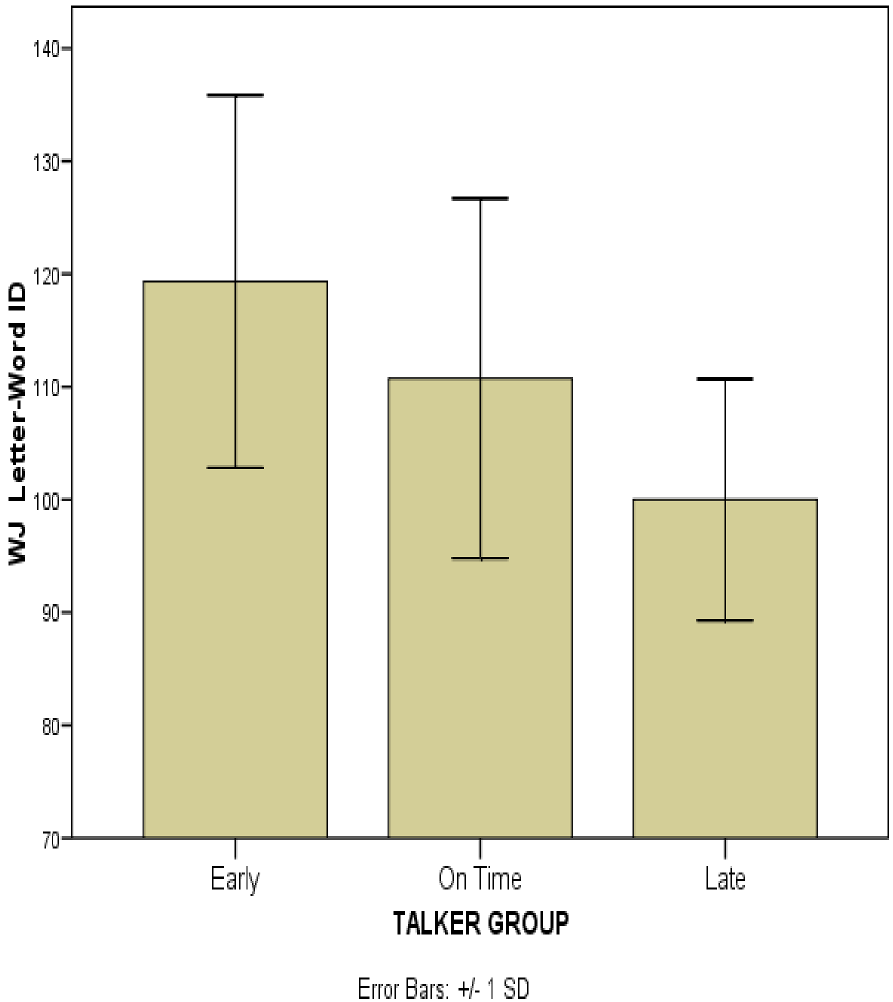
- Study 2) From 5-11 years examines brain/behavior trajectories in three languages that vary in orthographic depth (English, Finnish, Mandarin Chinese).

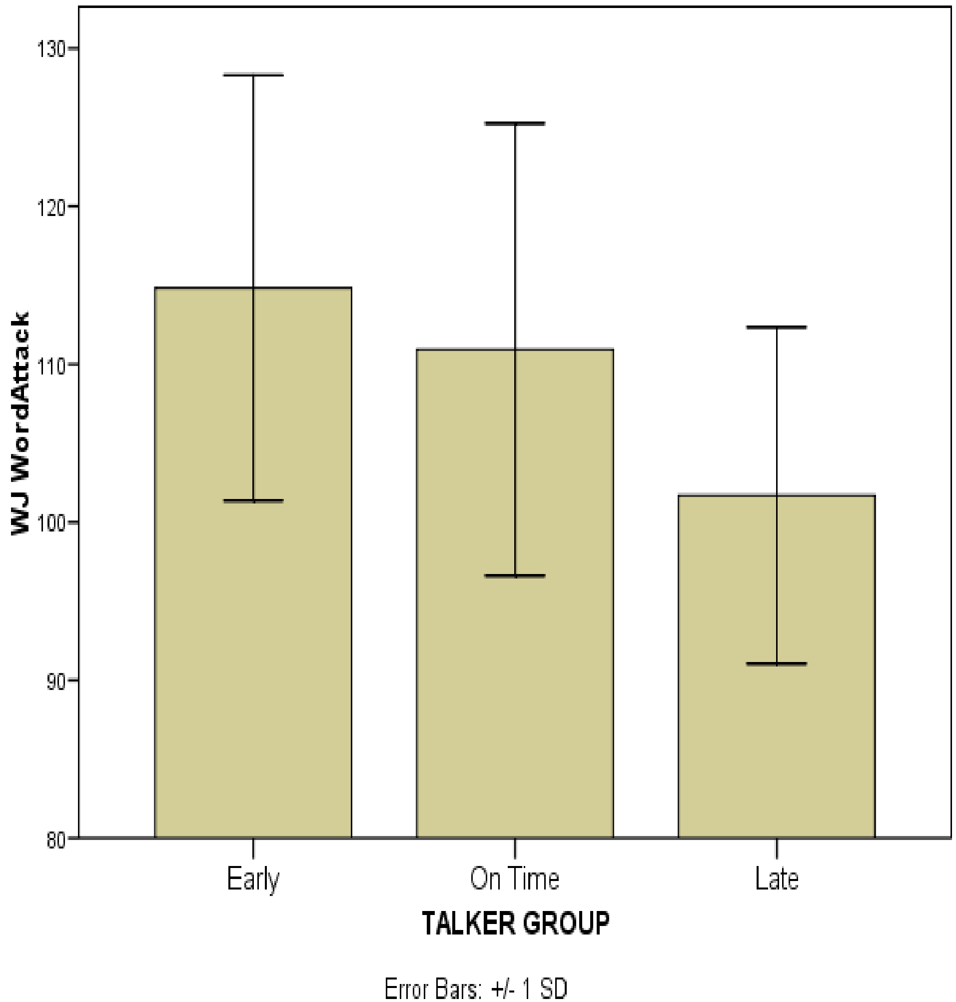
Effects of Early Language delays on reading at age 7 Preston et al., (2010 *Brain*)

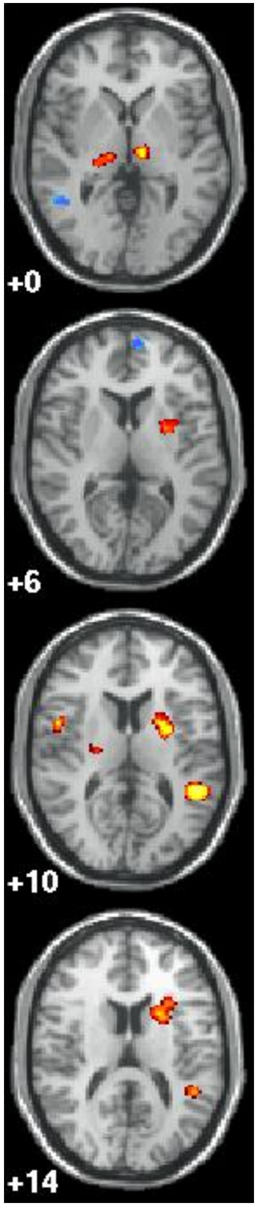
- Several studies of "late talkers" have suggested residual deficits in reading in young school-age children (Rescorla 2002, 2005, 2009; Scarborough & Dobrich, 1990)

- Parents complete questionnaire on child/family background and child's development
  - Asked to report on when child began to "Speak 2-3 word sentences."
  - Parent rated child as Early, On Time or Late

Talker Group Comparisons on Reading Measures: Woodcock-Johnson Tests of Achievement



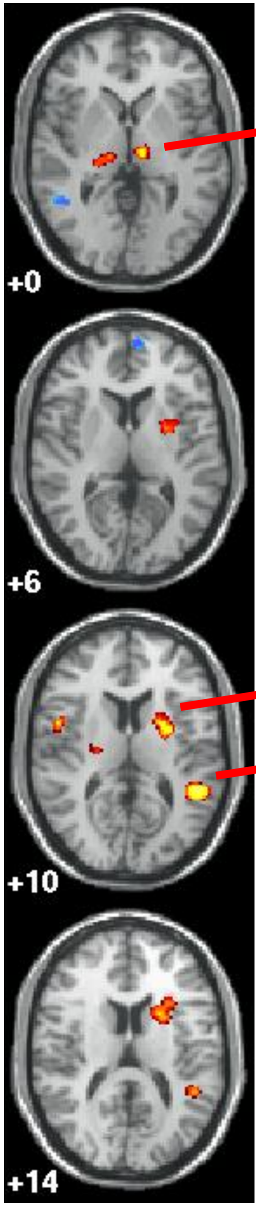




Late versus early talkers Brain activation in reading and speech at at 7.5

EARLY > LATE
LATE > EARLY

p < .025, FDR corrected



THALAMUS

PUTAMEN

SUPERIOR TEMPORAL GYRUS


+0
+6
+10
+14
SPEECH
PRINT
1.00
0.75
0.50
0.25
0.00
-0.25
Early
On Time
Late

Implications

These data suggest that late talking, along with its negative impact on reading scores, is associated with failure to develop subcortical (basal Ganglia and thalamus) and cortical circuits relevant to both reading and listening.

Implies an important, but still poorly understood, role for **motor learning** in the emergence of reading circuits.

May suggest an early “biomarker” for risk for language and reading difficulties.

The influence of phonological skills on the learning circuitry for print (Pugh et al., 2013, Brain and Language)

- Our major goal in this study is to identify brain pathways that are most strongly associated with individual differences on multiple indices of reading-relevant skills (phonological awareness, decoding, and auditory sensory processing) **at a point in time when the mature circuitry that will eventually come to support fluent reading is, to a large extent, still coming online.**

62 beginning readers (ages 5-8, mean = 7.7) ranging along a continuum from conventionally RD to superior readers.

- **Predictor tasks:**

  1) Phonemic Awareness (Elision; CTOPP)

  2) rapid auditory processing (TOJ Task)

  3) timed pseudoword reading (PDE; TOWRE)

- **Dependent measures:**

  1) Timed word reading (SWE;TOWRE)

  2) brain activation for print stimuli during fMRI

Behavioral Inter-correlations

	TOWRE PDE	CTOPP ELISION	TOJ ACCURACY	TOWRE SWE
TOWRE PDE	----			
CTOPP ELISION	.637**	----		
TOJ ACCURACY	.485**	.416**	----	
TOWRE SWE	.824**	.570**	.387*	----

*p<.01; **p<.001

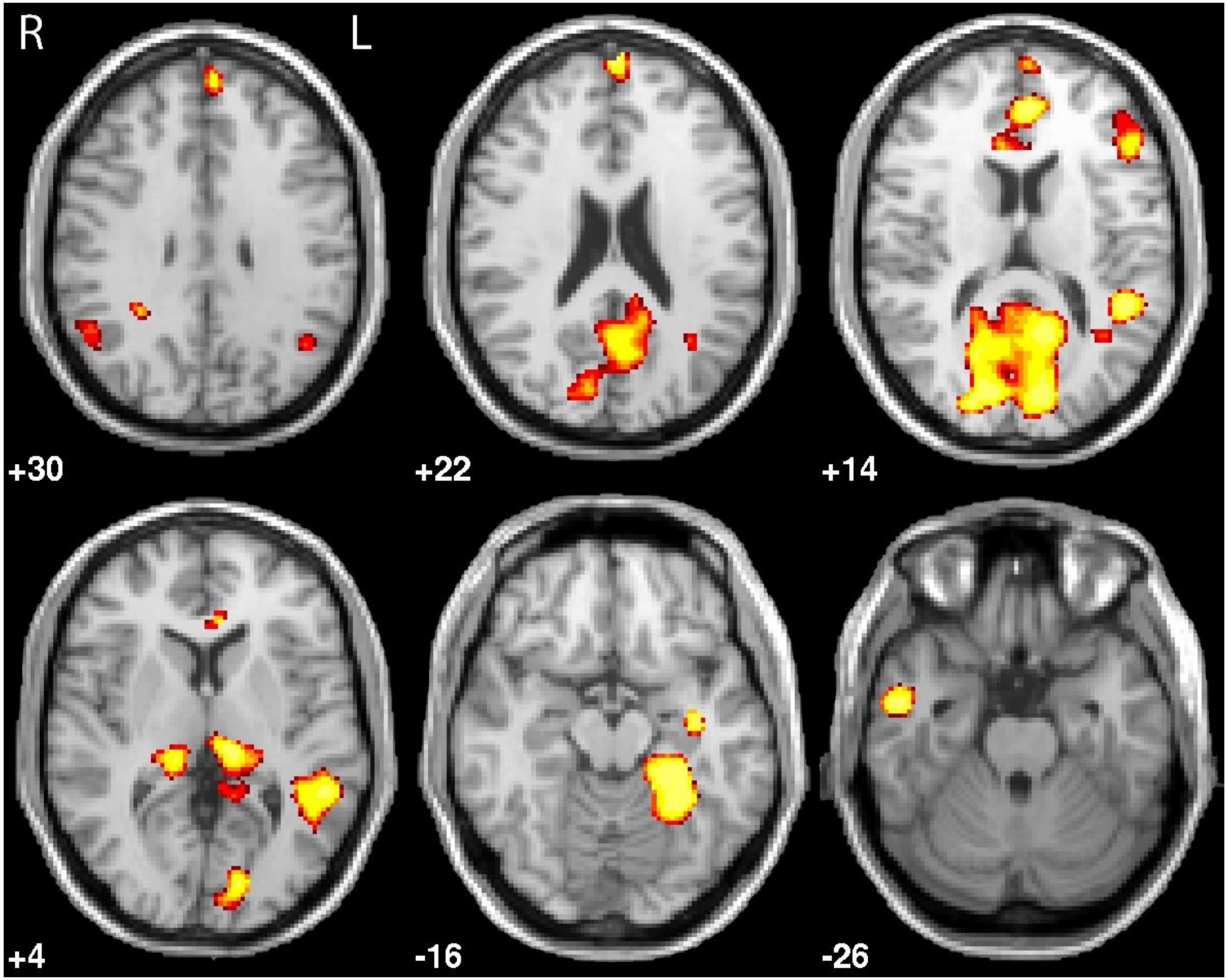
Brain-behavior analytic approach

- **Shared and unshared influences:**

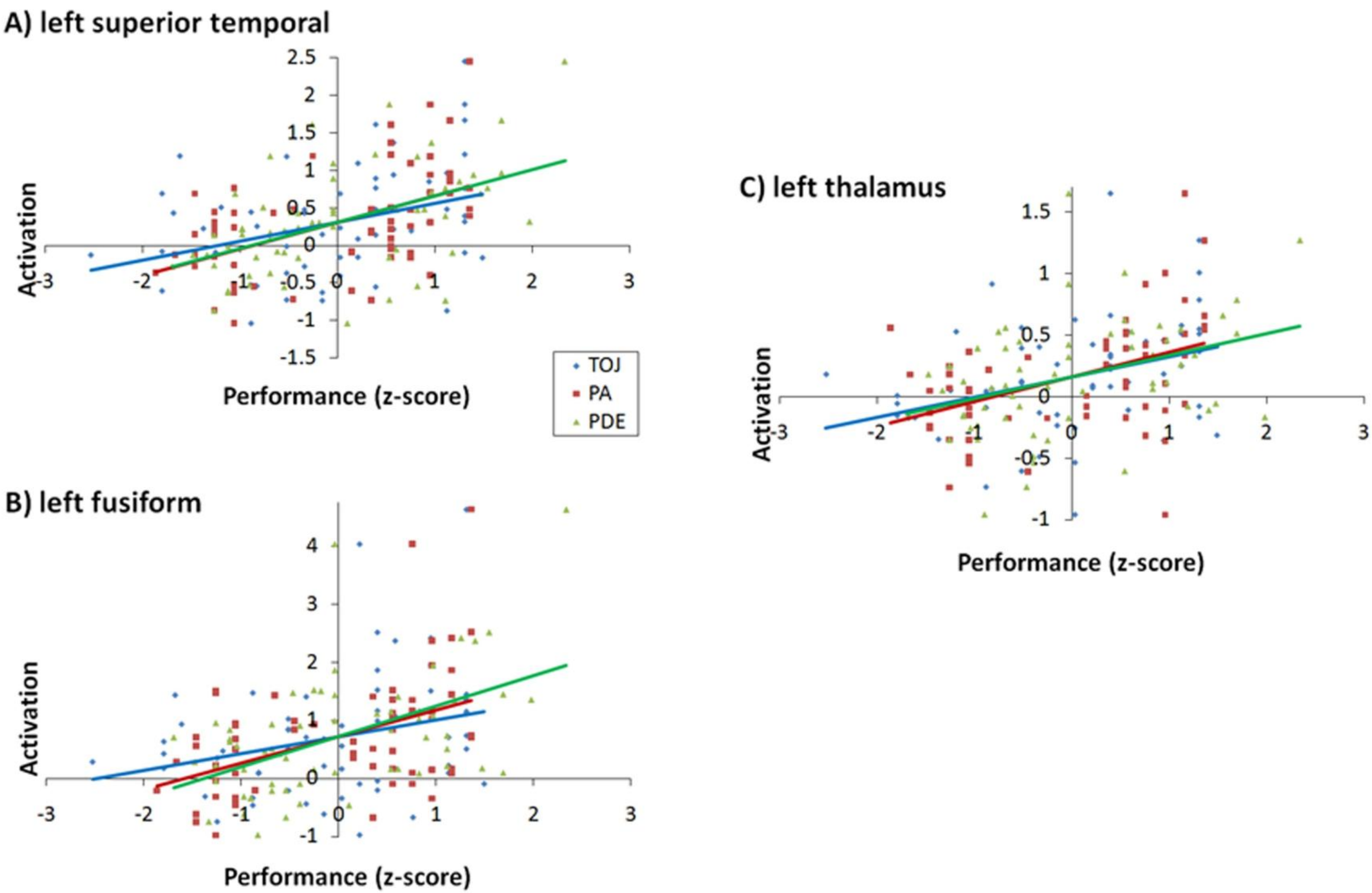
Given these correlations, we used PCA and partial correlation scores to determine whether these highly distinct tasks influence reading, and the neural pathways that support reading, via shared or unshared neurocognitive pathways.

- **For both PA and TOJ no unique influences of residual scores on behavior (or brain) were found.**
- **Thus the impact of these very different non-print tasks on print skills appears to be via common pathways.**

Correlation map of correlation between component scores and print activation



p<.01, FDR corrected


A) left superior temporal
B) left fusiform
C) left thalamus
Activation
Performance (z-score)
TOJ
PA
PDE

Print: Summary and discussion

The initial learning circuitry: For printed word and pseudoword processing, this brain-behavior analysis revealed links between variation in reading-relevant skills and neural responses in:

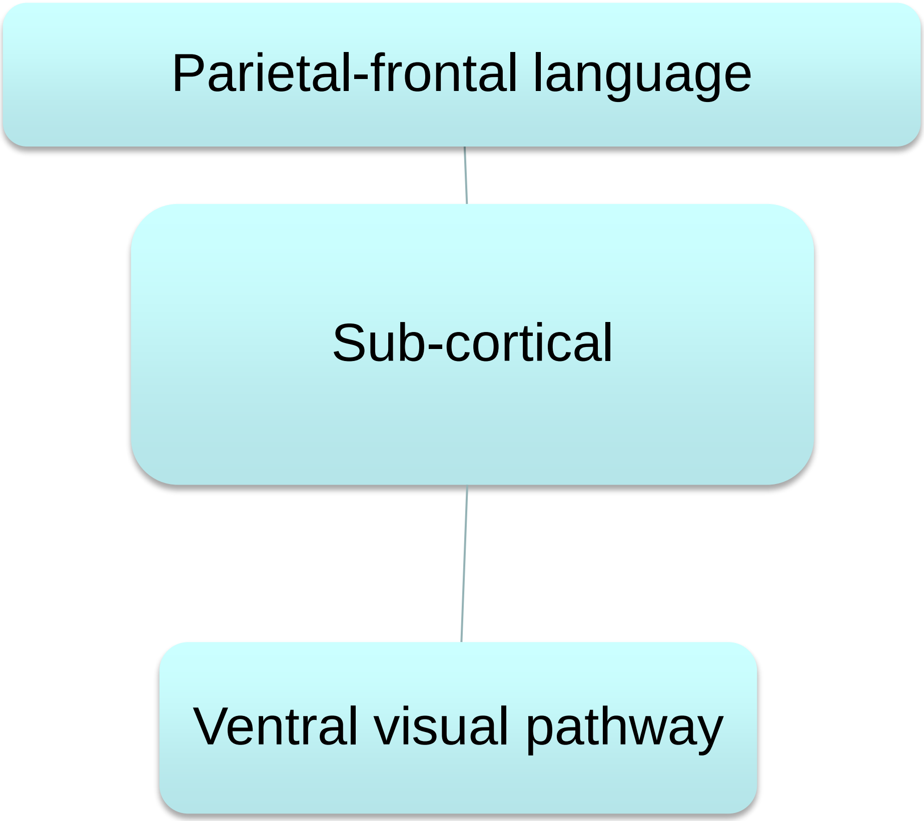
1) well-established cortical components of the LH circuit (TP, IFG and OT)

and

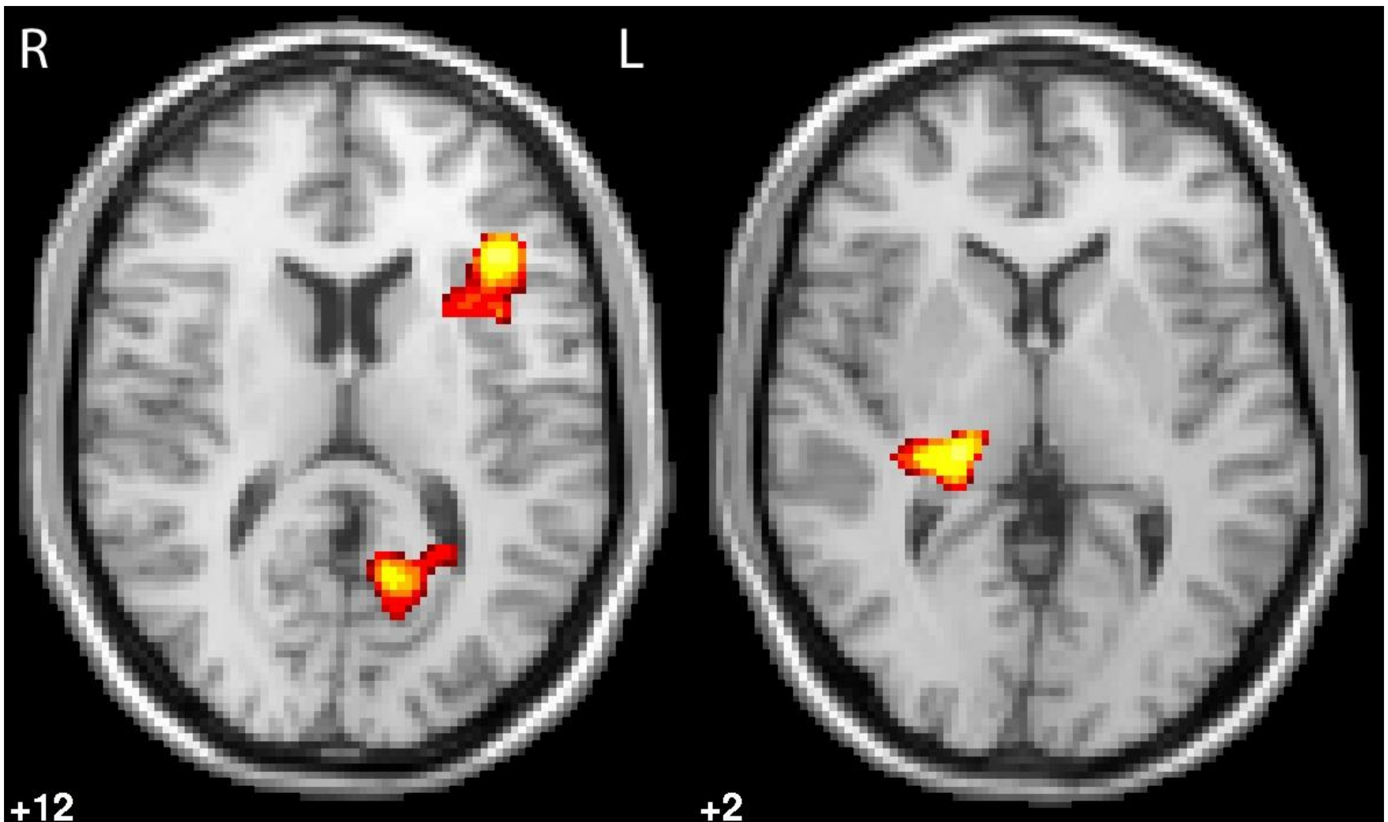
2) visual cortex including V1 and extrastriate areas, precuneus, thalamus (pulvinar), and RH regions including MTG and IPL.

Thalamus (pulvinar) Involvement: These data suggest a strong link between reading problems and thalamo-cortical pathways. Extrapolating from human and animal models of pulvinar function and connectivity (e.g., Serences & Yantis, 2006), we speculate that, in the context of learning to read, pulvinar mediates visual selective attention to those features that will shape emergent print specialization along the ventral visual pathway (especially the occipito-temporal cortex).

****Importantly, this brain/behavior analysis suggests that "training up" of ventral visual pathway is influenced by a distributed set of cortical regions sensitive to phonological form, including LH STG and IFG.**


Parietal-frontal language
Sub-cortical
Ventral visual pathway

Correlation map of correlation between component scores and spoken word activation



Feedback of reading skills on speech

For **spoken word and pseudoword processing**, brain-behavior analysis revealed links between reading-readiness scores and neural responses in speech motor regions (especially IFG).

Previous research that has found that speech motor involvement during speech perception tasks is greater when demands on segmental processing or attention to phonetic details are higher (Peschke et al., 2011; Zatorre et al., 1996).

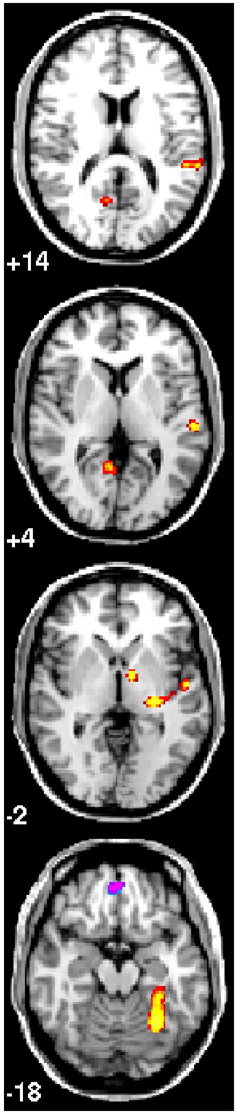
We speculate here that children further along the literacy curve are generally more focused on componential features in general, and this accounts for increased IFG involvement.

Effects of phonological skill on speech/print integration (Frost et al,. 2009)

•Phonemic awareness (PA) is the metalinguistic understanding that spoken words are made of smaller segments and this ability discriminates children at high or low risk for RD and scores on PA tasks reflect "reading readiness" in emergent readers.

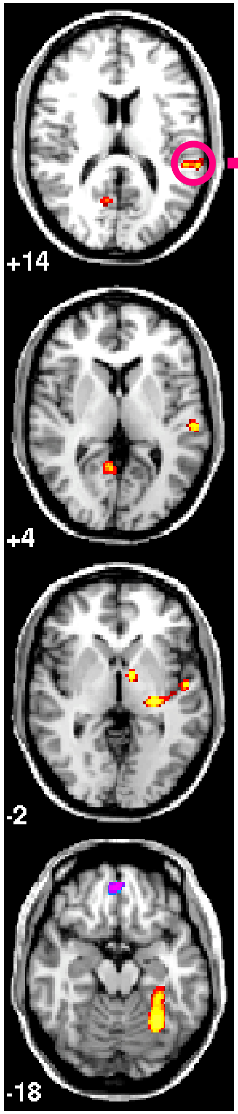
•How do beginning readers with higher or lower reading readiness as indexed by PA differ in early brain organization for spoken and written stimuli?

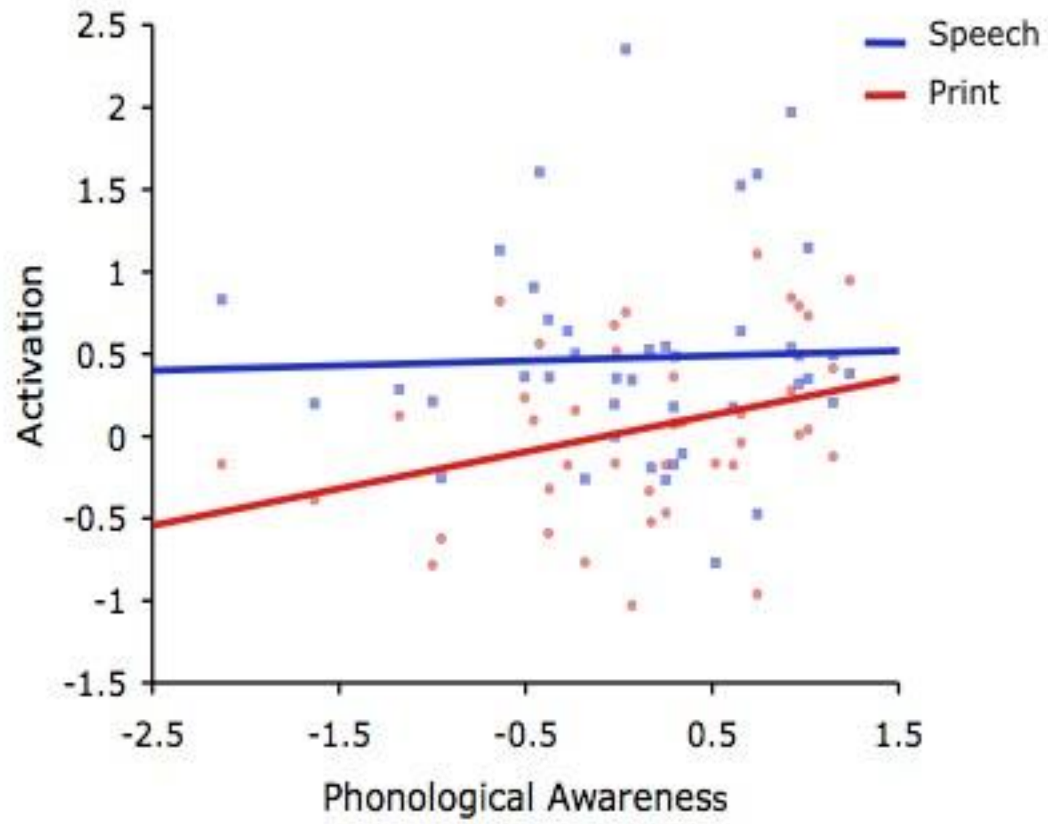
PA x Modality



$p < .01$

PA x Modality

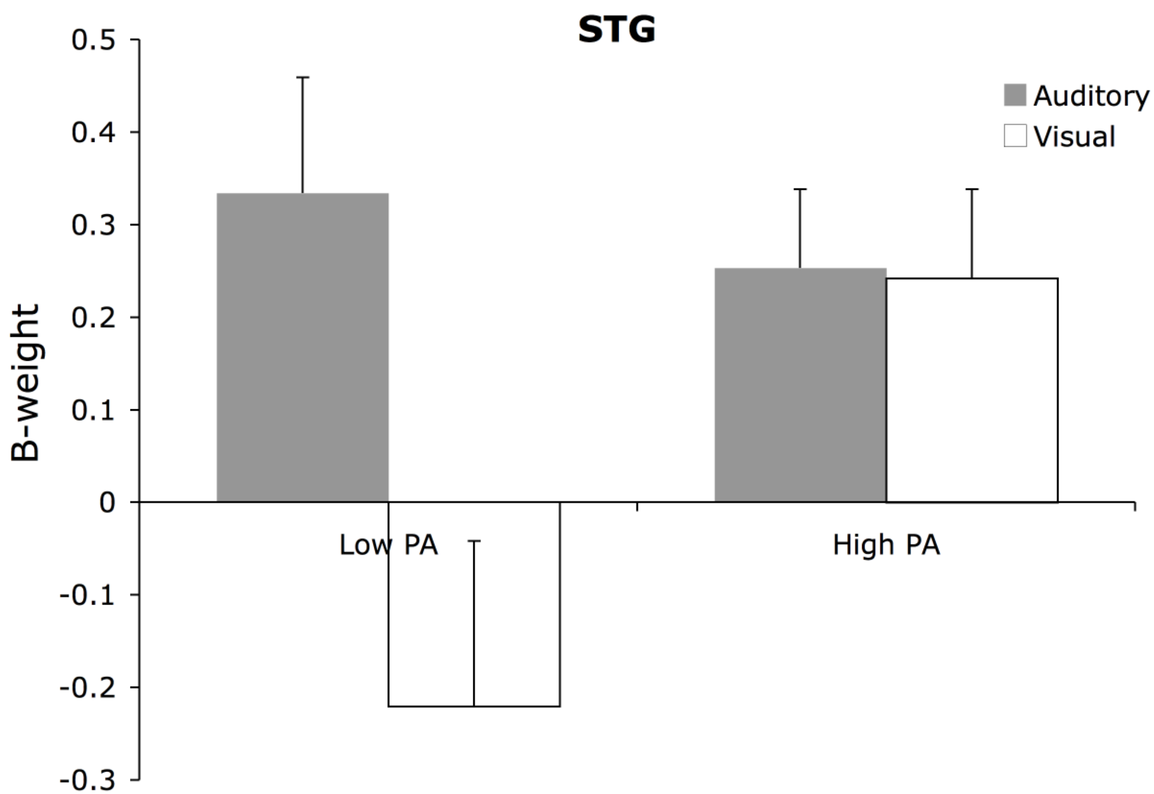




r = 0.44

p < .01

Correlation of PA with BOLD Modality Effect



Implications

- This finding suggests that children who are developing normally in reading modify speech attuned populations of neurons in STG to become available for processing visual graphemes.

Reading Comprehension and speech/print integration

- If comprehension is poor the reader may lack:

  a) Background knowledge and vocabulary?

  b) Requisite language abilities?

  c) Sufficient word decoding skills?

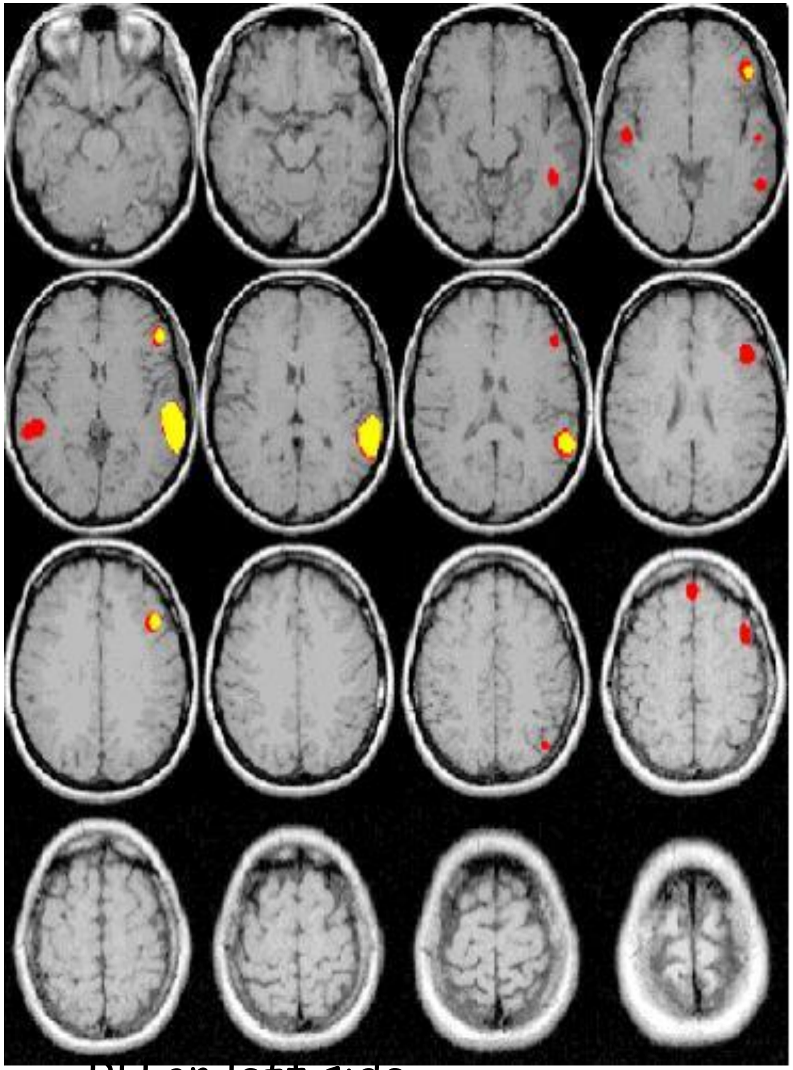
  d) Some combination of a, b, and c.

- **Reading is possible because the language brain is supramodal:**

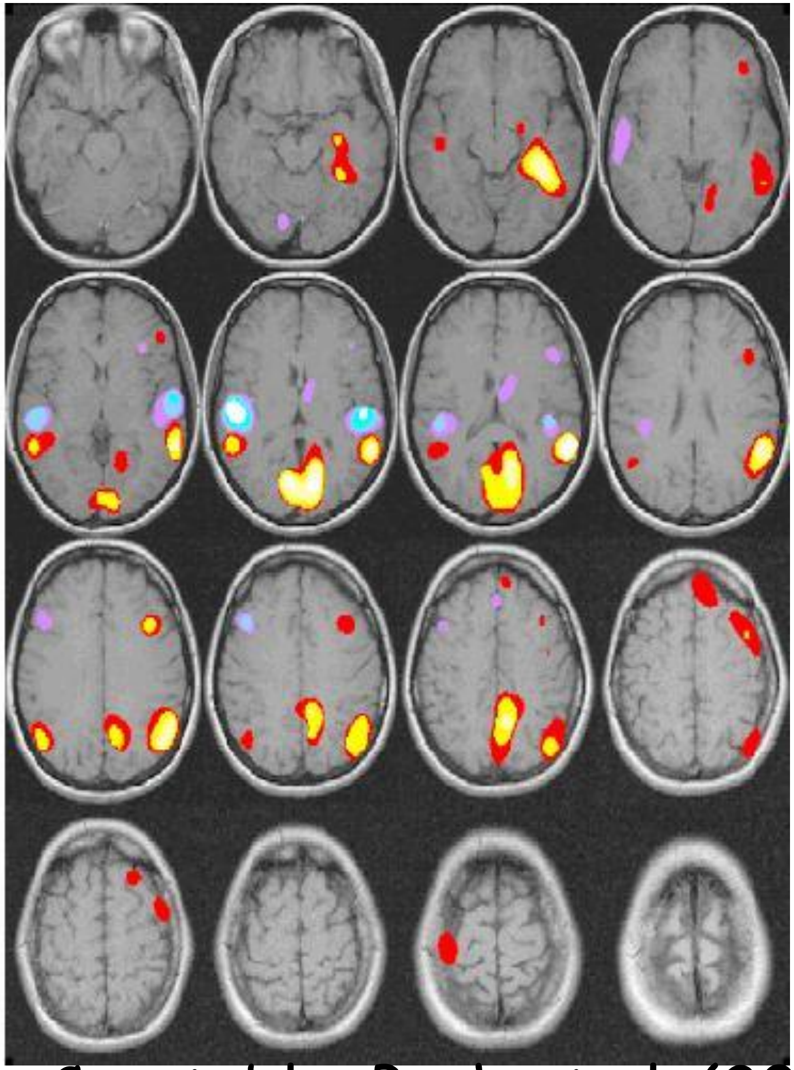
  Where do speech and print streams merge during sentence processing?

Auditory vs Visual Sentence Task

common **print(red) speech(blue)**



RH on left side

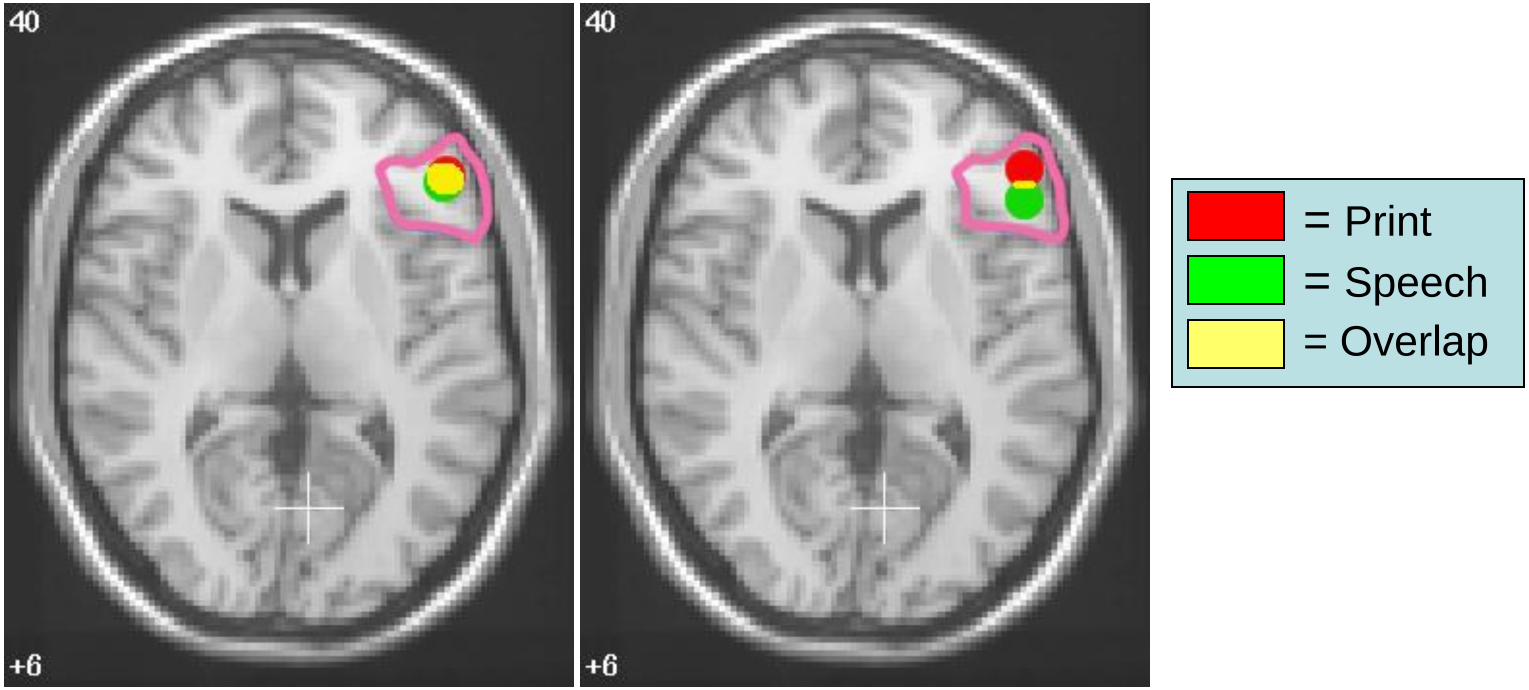


Constable, Pugh et al. (2004)

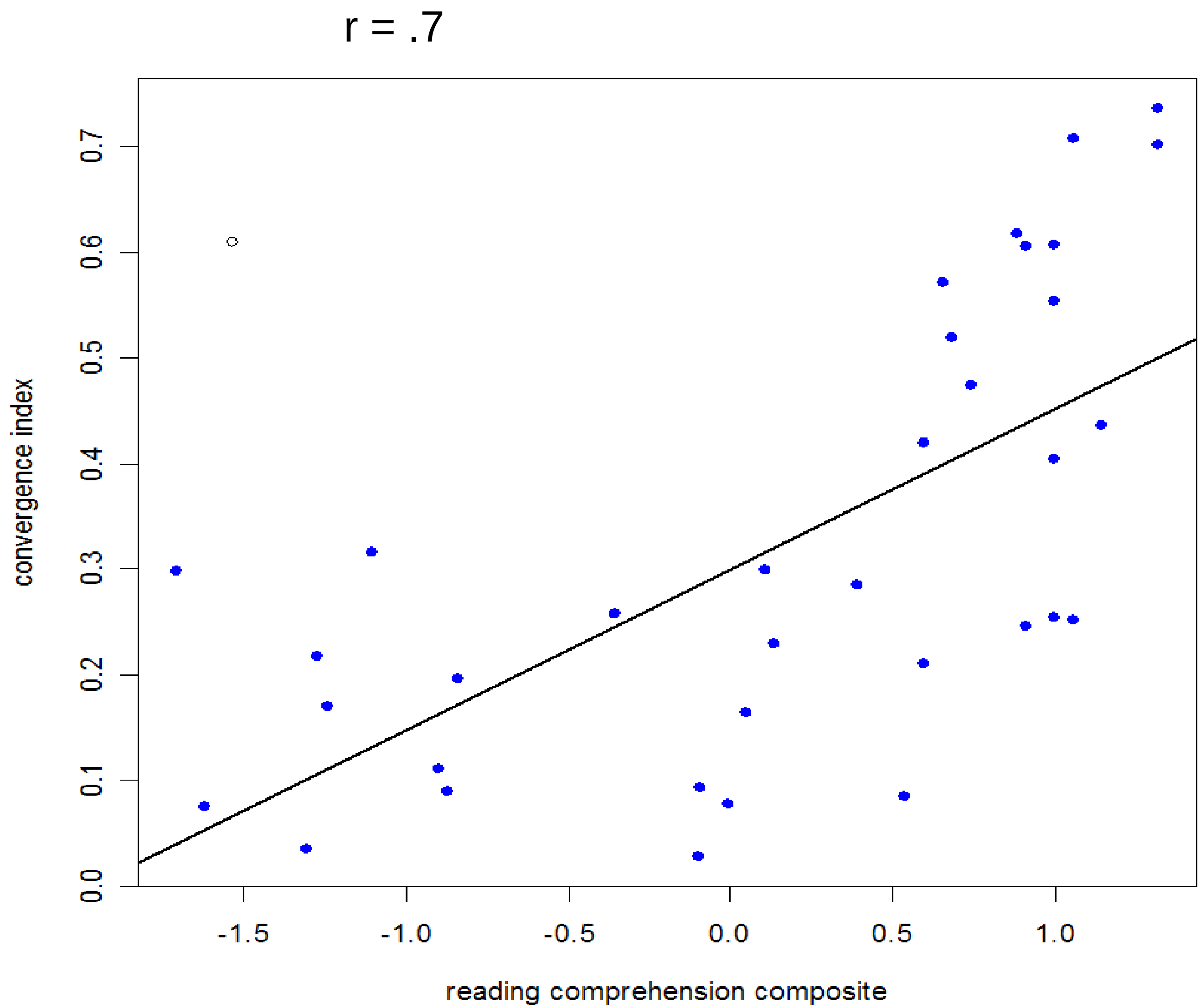
- **fMRI Sentence processing study (Shankweiler et al., 2008).**

1. Does convergence co-vary with reading skill?

Illustrating high and low values of the Convergence Index



Correlation of convergence and skill at dorsal IFG



Summary: Cross modal integration and reading skill

- These studies in English indicate that both at the level of word recognition and at the level of sentence processing a critical factor discriminating skilled from less skilled readers is the degree of print/speech integration in relevant LH circuits.

- Is there a parallel relation in non-alphabetic orthographies?

Cross language reading research

- Big question: Is there a universal reading circuitry?

- What is the role of speech/print integration in languages differing in orthographic depth?

Division of Labor: Cross Language

Orthographic depth hypothesis (R. Frost & Katz and others):

More transparent O-P mapping, greater reliance on O-P pathway

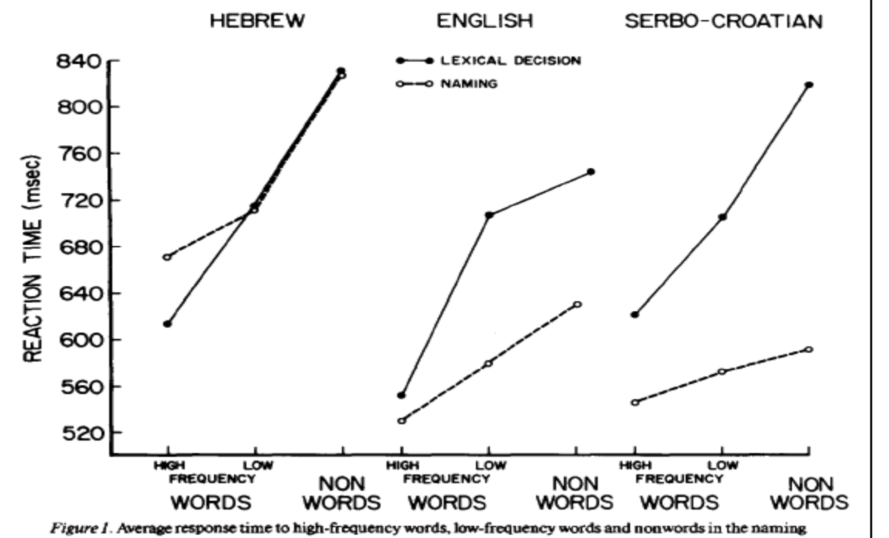
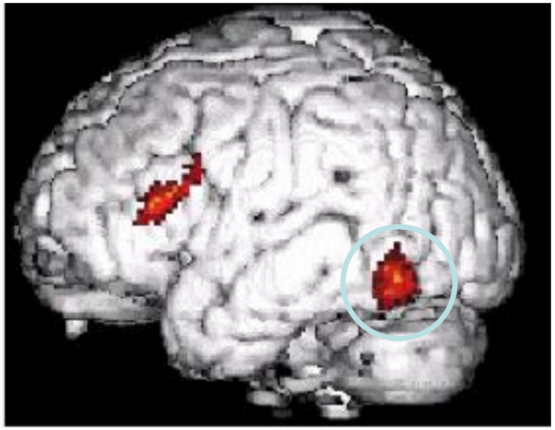


Figure 1. Average response time to high-frequency words, low-frequency words and nonwords in the naming task (dashed line) and in the lexical decision task (solid line) in Hebrew, English, and Serbo-Croatian.

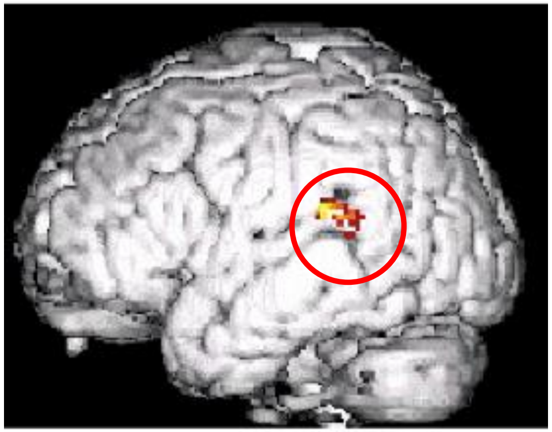
Frost, Katz, & Bentin (1987)

Cultural (orthography) differences in reading

English (Deep)



Italian (Shallow)



Paulesu et al., 2000

Differential weighting of brain areas for English as compared to Italian

Shallow orthography – one to one mapping - Dorsal
Deep orthography – many to one mapping of letters to sound – Ventral

Neuroanatomical Correlates of Phonological Processing of Chinese Characters and Alphabetic Words: A Meta-Analysis

Li Hai Tan,[1*] Angela R. Laird,[2] Karl Li,[2] and Peter T. Fox[2]

[1]Cognitive Neuroscience Laboratory, Department of Linguistics, University of Hong Kong, Pokfulam Road, Hong Kong
[2]Research Imaging Center, University of Texas Health Science Center at San Antonio, San Antonio, Texas

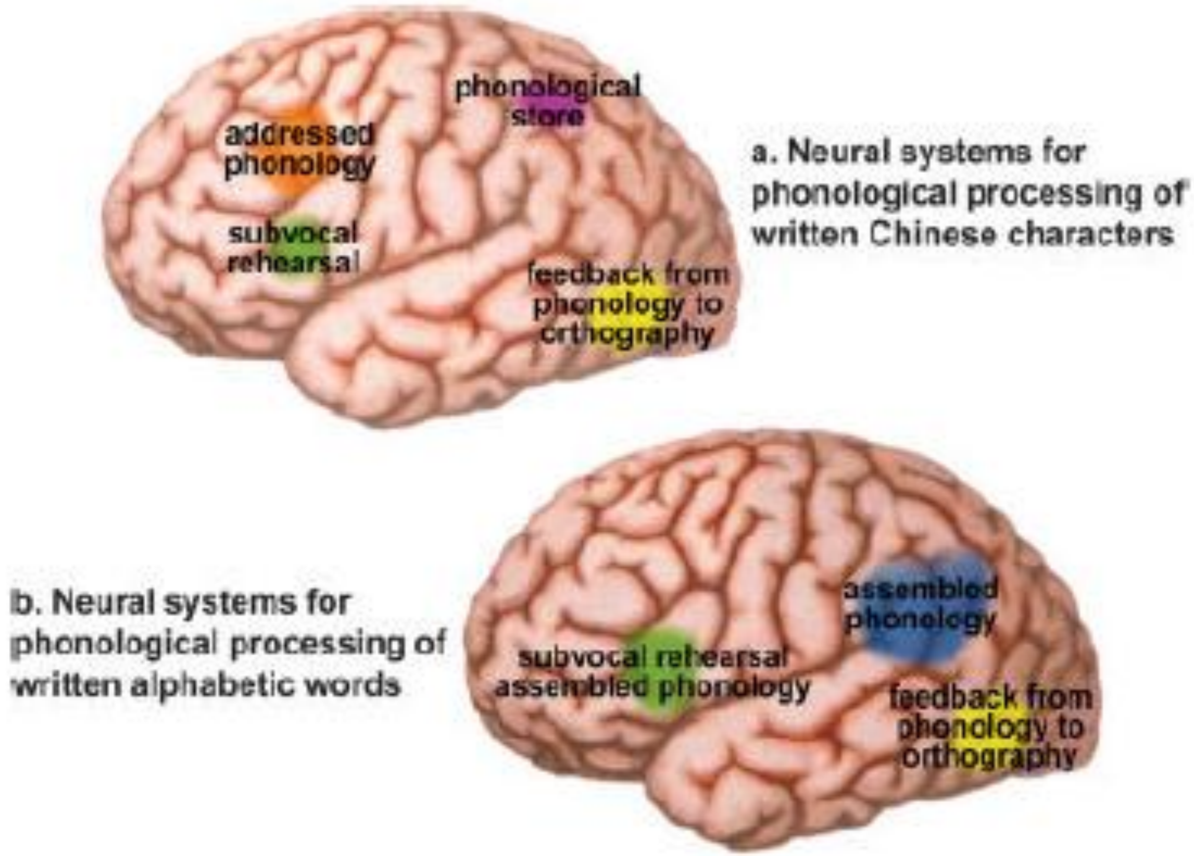


Figure 2.
Neural systems for phonological processing of Chinese characters and alphabetic words.

The Haskins, BCBL, Hebrew University, National Central University ICN Project

- How does variation in orthographic depth modulate neurocircuits for reading?

- How does variation in orthographic depth modulate the overlap between circuits engaged for reading and speech?

- How does visual masking modulate the print-speech relation across orthographies?

Collaborators on this study

Haskins

Pete Molfese

Jason Zevin

Einar Mencl

Ken Pugh

Jay Rueckl

Laura Mesite

BCBL, Spain

Kepa Paz-Alonzo

Manuel Carrieras

Hebrew University, Israel

Atira Bick

Ram Frost

National Central University, Taiwan

Denise Wu

Nissen Kuo

Jun Ren Lee

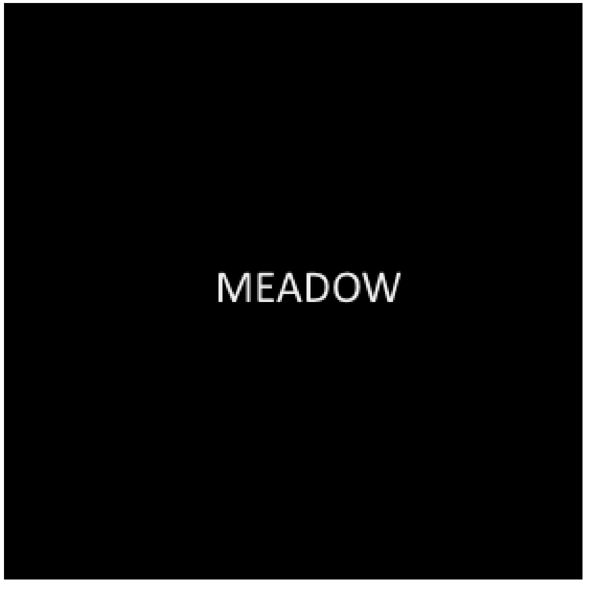
Ovid Tzeng

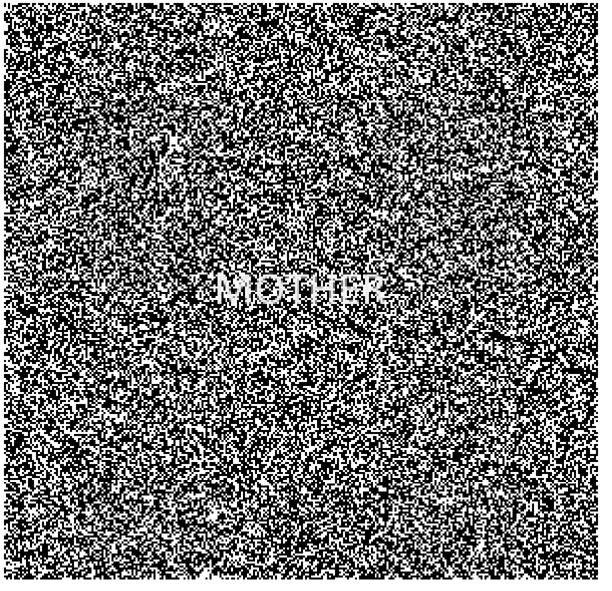
And many others….

Funding from NIH P01 HD001994

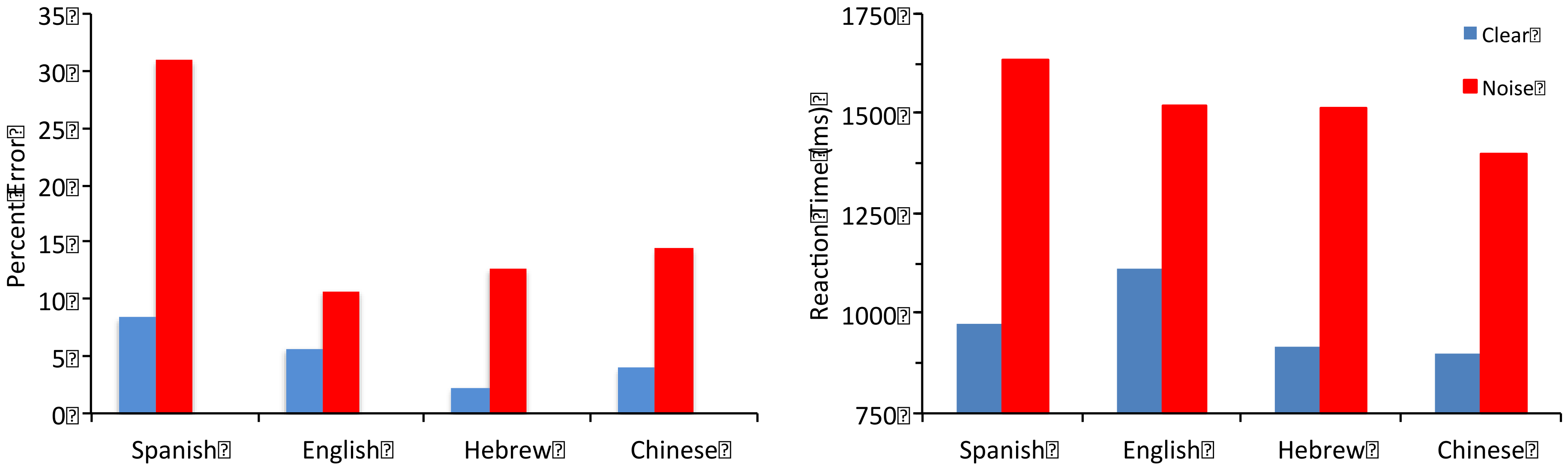
Basic Design

- Hybrid block/event-related design
- Participants make animacy (living or non-living) judgments to high and low frequency printed words presented in the clear or embedded in visual noise.
- Animacy judgments are also made to spoken words in the clear to localize speech regions

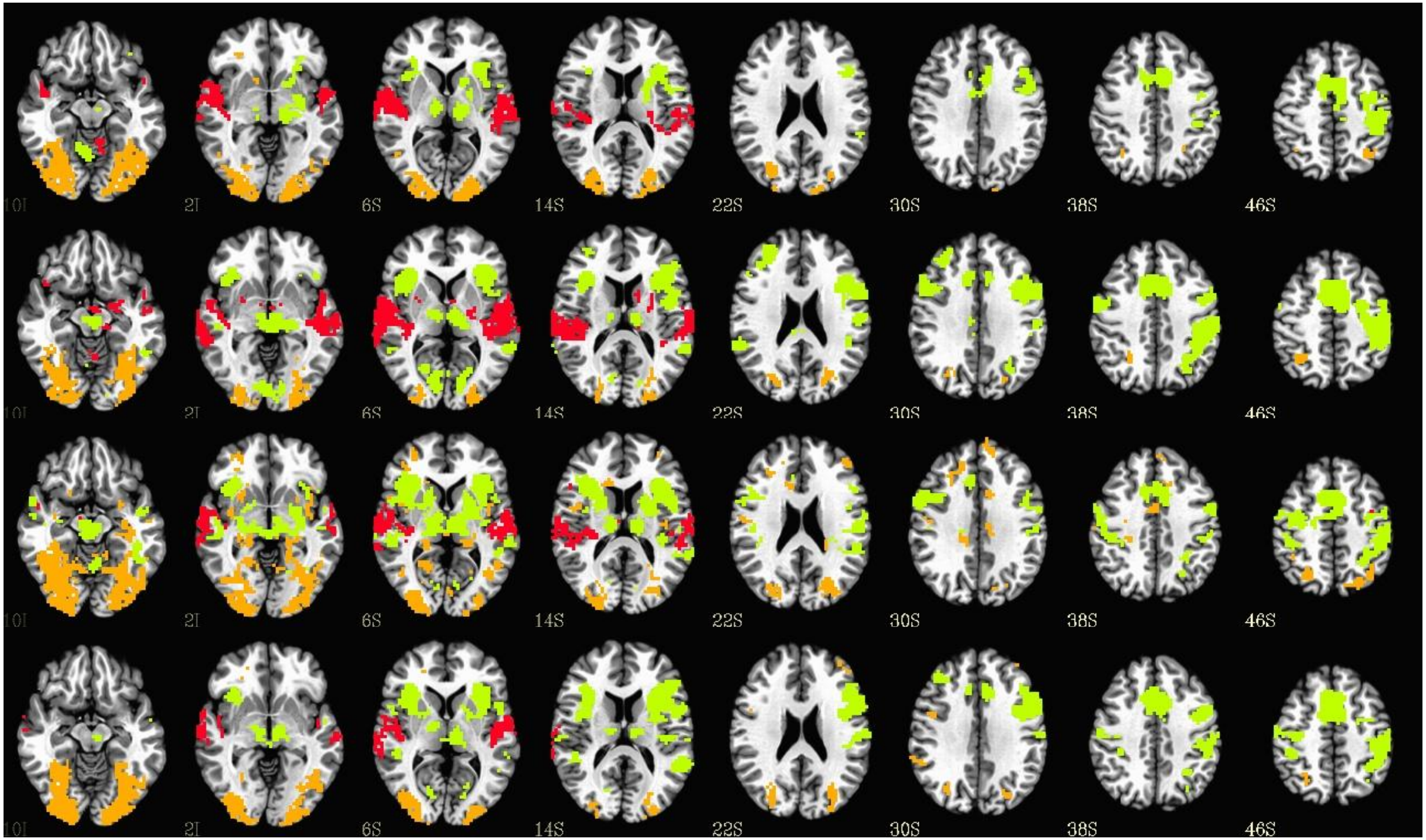




In-scanner Behavior

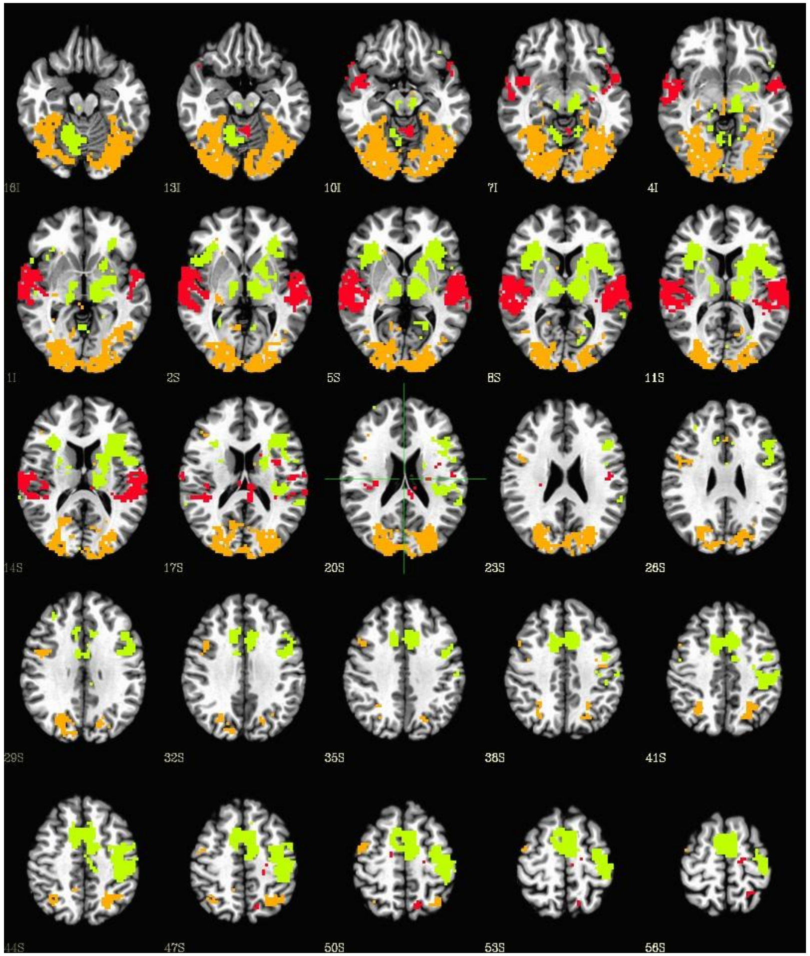


Modality Intersects



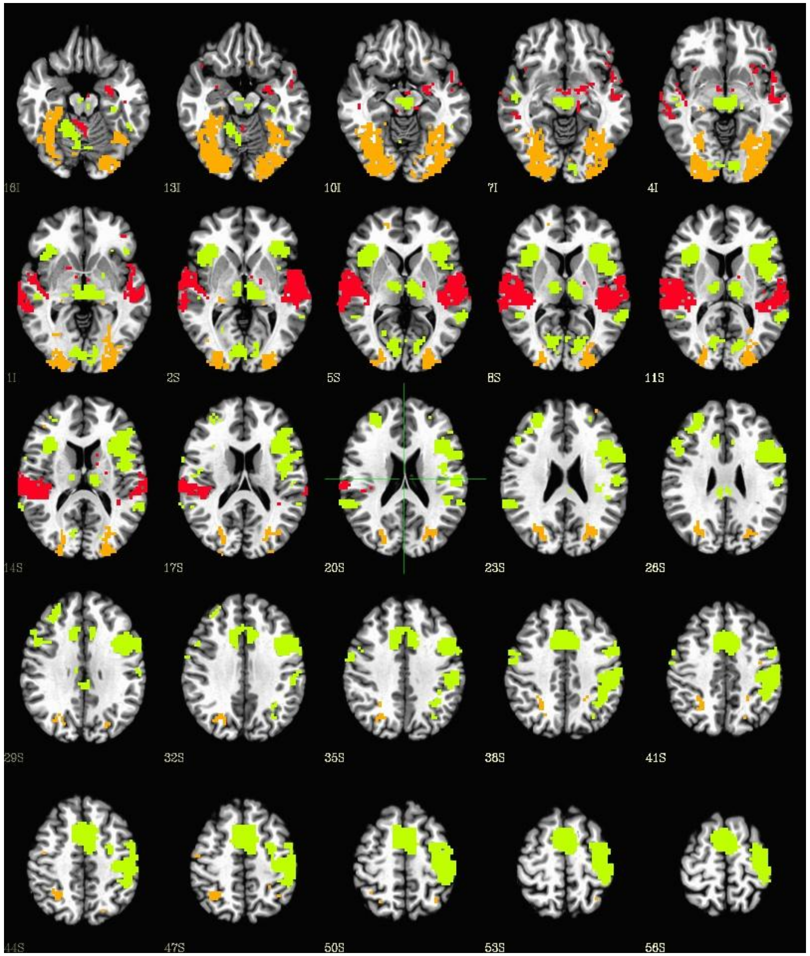
Orange = Visual; Red = Auditory; Green = Auditory + Visual

Chinese Data



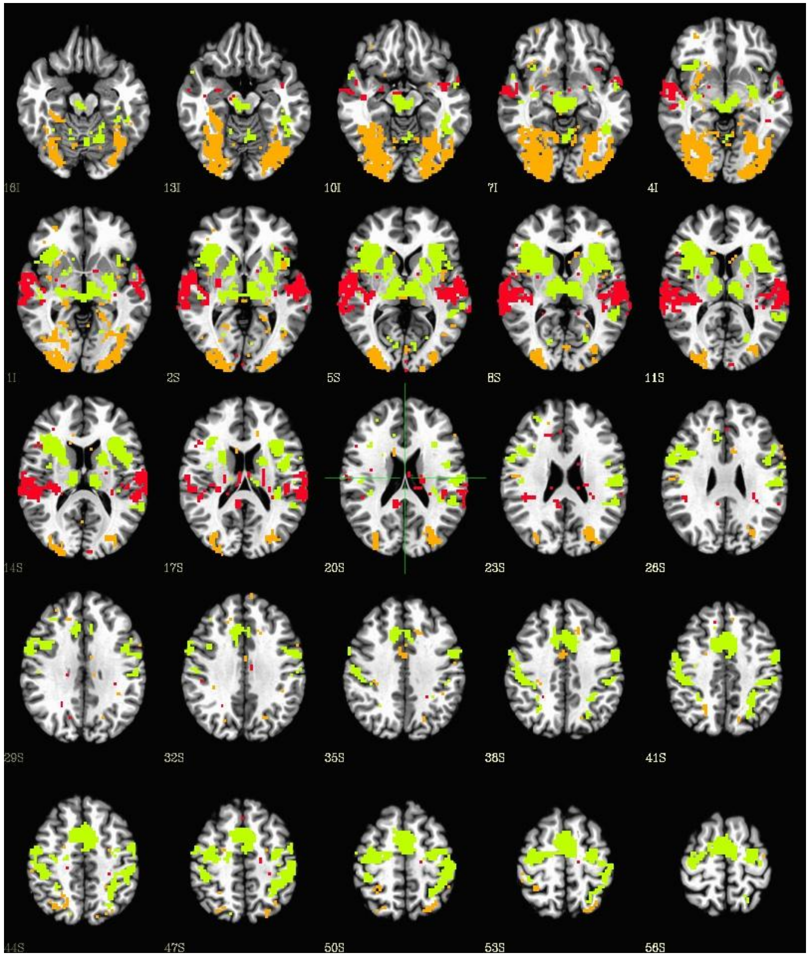
Orange = Visual; Red = Auditory; Green = Auditory + Visual

English Data



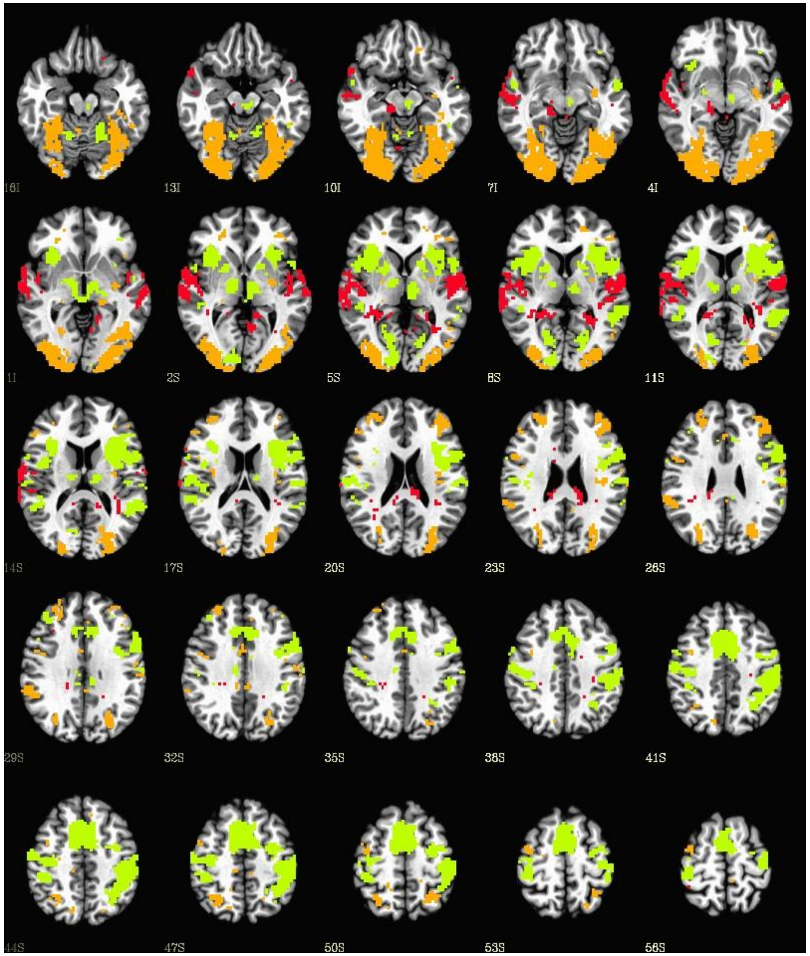
Orange = Visual; Red = Auditory; Green = Auditory + Visual

Hebrew Data



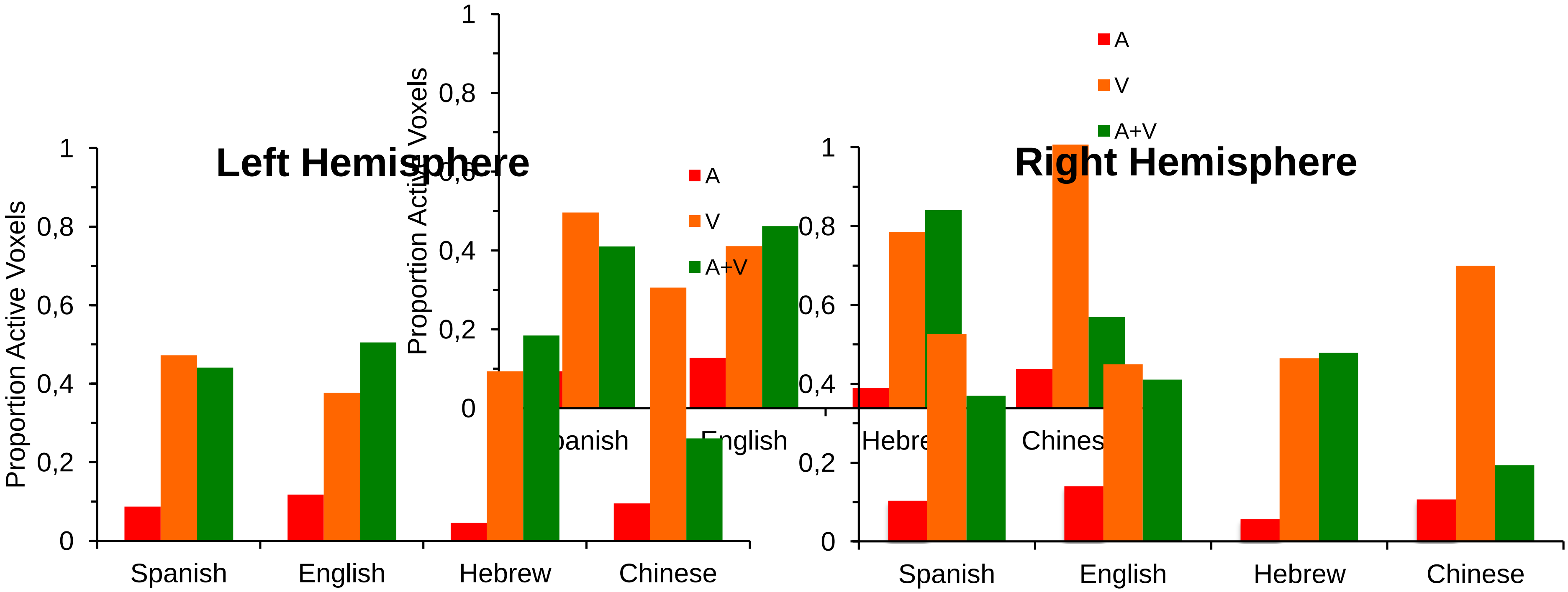
Orange = Visual; Red = Auditory; Green = Auditory + Visual

Spanish Data

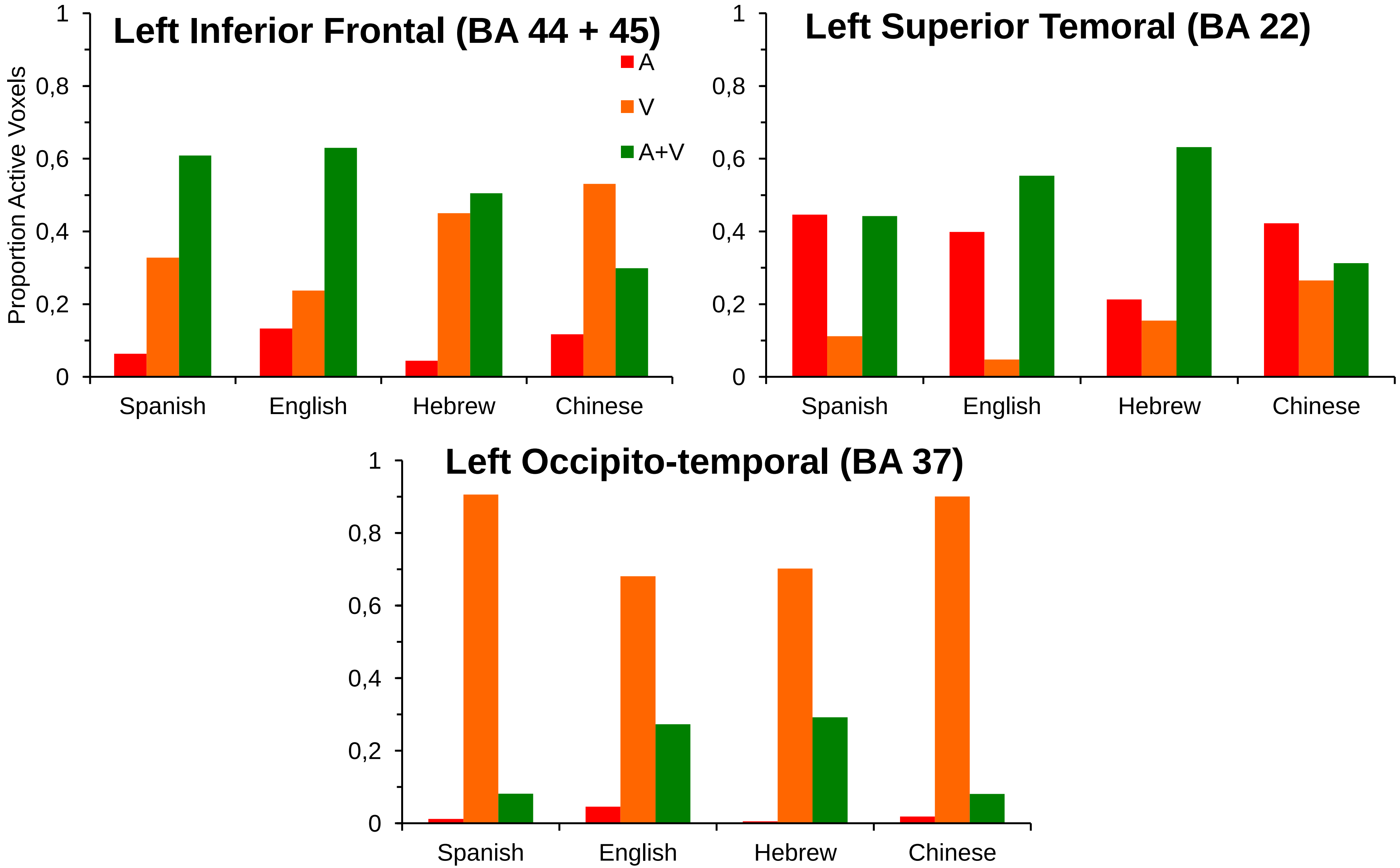


Orange = Visual; Red = Auditory; Green = Auditory + Visual

Pattern of print-speech convergence



Regions of Interest

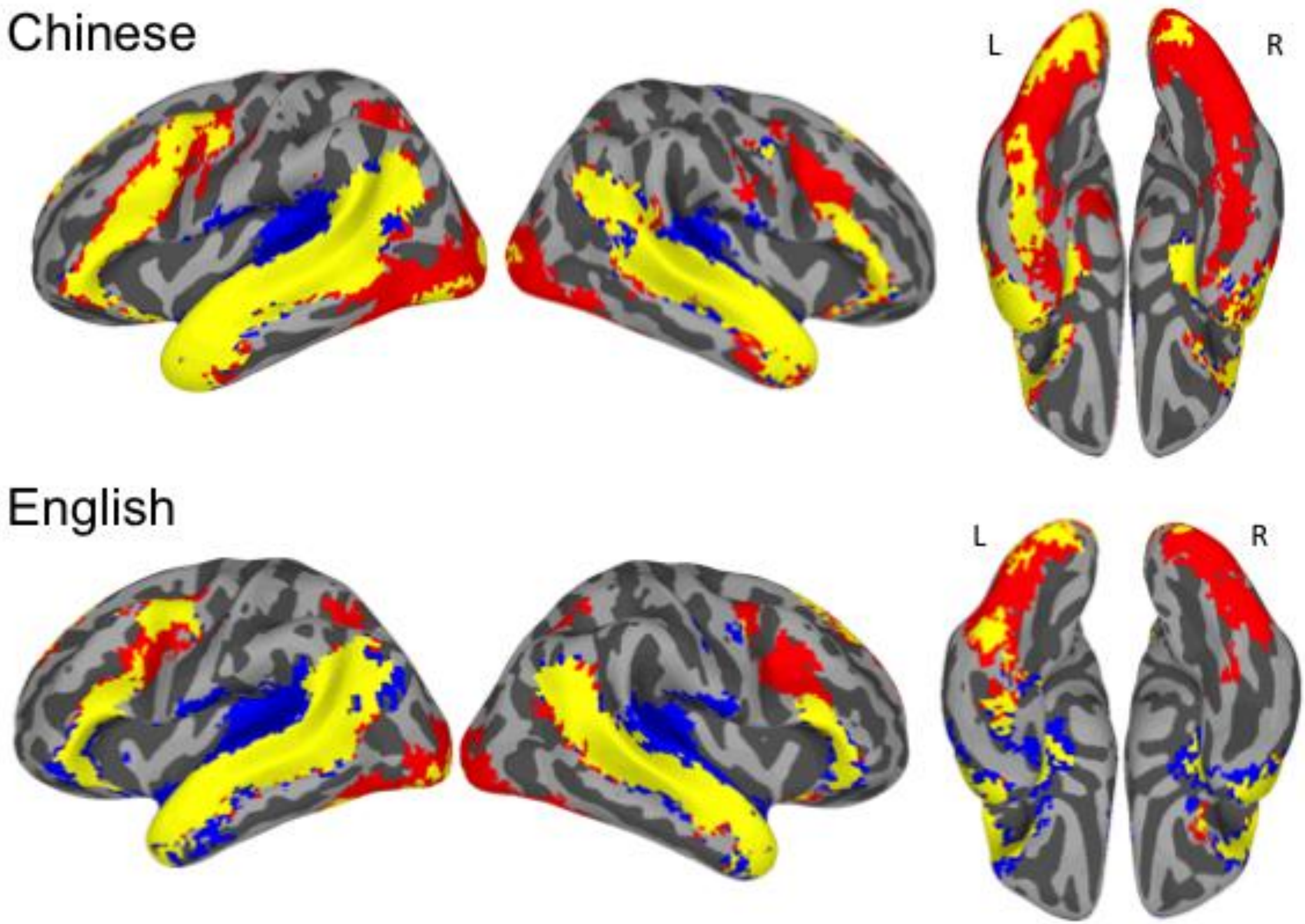


How different are Chinese and English in “naturalistic” tasks?

Reading vs. listening to stories (Zevin et al., submitted)

- Zevin hypothesizes that some of the cross language differences in speech and reading for Mandarin vs. English could arise from the kinds of cognitive tasks (e.g., lexical decision, rhyme judgment, etc.) that we employ.
- So in this study participants either listen to or read stories with a Chinese and English group contrast

三根羽毛	“Three feathers”
从前有一位老国王，	There was once an old king
他有三个儿子。	He had three sons.
老大和老二精明干练，	The eldest two were smart and capable
老三心地单纯，	The youngest had a pure heart,
大家都叫老三“傻子”。	and people all called him "fool".
老国王一直不能确定	The old king had been unable to determine
把王位传给谁，于是，	who should become the king after him, therefore,
他把三根羽毛吹向空中，说：	he blew three feathers into the air and said:
“往羽毛飞的方向走吧！	"Go in the direction the feathers fly to!
你们之中谁能找到	Whoever finds
世界上最精美的地毯，	the world's most beautiful carpet,


Chinese
L
R
English
L
R

Implications

- Universal reading brain? Maybe.

- Cross-language similarities outweigh differences

- Regional differences in print-speech convergence will need to be understood and how they relate to the computational roles of the regions across languages

- Next steps: Test all this in emergent readers

Haskins NICHD P01:The nature and acquisition of the speech code and reading

Continuing a long-standing goal in this Program to explicate important links between speech and reading in the new cycle we focus pre-school children. We ask:

1) how sensorimotor systems associated with speech perception and production support the development of age-appropriate phonological (and subsequent) orthographic learning.
2) 2) how becoming print-literate feeds back upon and modifies speech perception and production.
3) 3) how these relationships differ across contrastive orthographies (Spanish, English, Mandarin).

Core hypothesis tested in this longitudinal study

- We propose (and test) a brain-based speech motor theory that traces meta-phonological learning in pre-school and later reading deficits to early problems in speech perception, production, and especially in perception/production dynamics/interactions.
- With respect to cross-linguistic comparisons we propose a universality in links between speech/motor processing and reading

Key Collaborators

- **Haskins Laboratories**: Einar Mencl, Stephen Frost, **Rebecca Sandak**, Nicole Landi, Leonard Katz, Jay Rueckl, Ram Frost, Jim Magnuson, Elena Grigorenko, Robert Fulbright, Jon Preston, Ram Frost, Donald Shankweiler, Jun Ren Lee, Ovid Tzeng, Denise Wu, Nissan Kuo, Mark Seidenberg, Jason Zevin, Julie Van Dyke, Daragh Sibley, Peter Molfese,